Balanced Mixture Design Implementation Support

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16. Abstract

This project sought to evaluate performance-based methodologies for asphalt mix design and develop a preliminary balanced mix design (BMD) specification for the Wisconsin Department of Transportation (WisDOT) projects. The work plan included conducting a literature review, interviewing Wisconsin mix designers, conducting a BMD workshop, benchmarking existing WisDOT mix designs, modifying selected mix designs for improved performance, and conducting cost analysis of mix design modifications. Mixture performance tests included the Hamburg Wheel Tracking Test (HWTT) to evaluate mixture rutting and moisture resistance, the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) for the evaluation of intermediate-temperature cracking resistance, and the Disc-shaped Compact Tension (DCT) test for the evaluation of low-temperature cracking resistance. A database of mixture performance test results was developed in the benchmarking experiment and preliminary performance test criteria were suggested for WisDOT mixes. The impacts of common mix design variables on the mixture performance test results were evaluated and several successful mix design modification strategies were identified. A simple cost analysis of the mix design modifications to improve five poor-performing mixes indicates that the materials cost could increase by approximately 8 to 22% to meet the proposed performance test criteria. Asphalt contractors are suggested to explore different mix design modification strategies so that they can determine the most cost-effective options for their materials. Finally, suggested modifications to the WisDOT standard specification for the initial implementation of BMD for MT, HT, and SMA mixes are provided.

17. Key Words Asphalt mixtures, balanced mix design, Hamburg Wheel Tracking Test, Indirect Tensile Asphalt Cracking Test, Disc-shaped Compact Tension test, mix design modification, cost analysis, WisDOT standard specification.	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road, Springfield, VA 22161

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EXECUTIVE SUMMARY

Like many other state highway agencies, the Wisconsin Department of Transportation (WisDOT) has been concerned with the durability and cracking issues of asphalt mixtures designed with the Superpave mix design approach. To address these issues, WisDOT started implementing the regressed air voids approach in 2017, which was proved effective in improving mixture cracking resistance without compromising rutting resistance in WHRP project 0092-16-06. However, even with the improvements, this modified Superpave mix design approach still has significant limitations that hinder innovations and lead to an unacceptable range of field performance for current asphalt paving mixtures. Therefore, WisDOT has interest in implementing mixture performance tests for balanced mix design (BMD) that will better assess the resistance of asphalt mixtures to common distresses and enable mix designers to better utilize sustainable and innovative materials.

The objective of this research project was to evaluate performance-based methodologies for asphalt mix design with the intent of developing a preliminary implementable BMD specification for WisDOT projects. To that end, a comprehensive work plan was proposed and executed, which included conducting a literature review, interviewing Wisconsin mix designers, conducting a BMD workshop, benchmarking existing WisDOT mix designs, modifying selected mix designs for improved performance, and conducting cost analysis of mix design modifications. The mixture performance tests used in the project were the Hamburg Wheel Tracking Test (HWTT) to evaluate mixture rutting and moisture resistance, the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) for the evaluation of intermediate-temperature cracking resistance, and the Disc-shaped Compact Tension (DCT) test for the evaluation of low-temperature cracking resistance.

Major findings of this project are summarized as follows:

- **Mix Designer Interviews.** At the time of the interviews, BMD test equipment was not widely available among asphalt contractors and testing labs in Wisconsin. Only a few of them had experience in conducting a complete BMD. Most mix designers indicated that they would first consider increasing the asphalt binder content and reducing the recycled asphalt material (RAM) content to improve mixture cracking resistance, while other possible adjustments reported include using a softer virgin binder and adding a recycling agent. Mix design modifications suggested to improve mixture rutting resistance include coarsening the aggregate gradation, increasing angularity of the aggregates, increasing the RAM content, and using a polymer modified binder. There was no consensus on which of the current Superpave volumetric criteria could be relaxed or eliminated for BMD. Although the mix designers recognized the benefits of implementing BMD, they also expressed concerns about the selection of performance tests and criteria, changes to the current practice with asphalt mix design and quality assurance, and several other implementation challenges.
- **Benchmarking Experiment.** A database of HWTT, IDEAL-CT, and DCT test results was developed for 18 WisDOT mixes covering a range of traffic levels, aggregate sizes,

aggregate types, and RAM contents. The database was analyzed to determine distributions of results for HWTT corrected rut depth at 20,000 passes (CRD_{20k}) and stripping number (SN), IDEAL-CT cracking tolerance index (CT_{Index}), and DCT fracture energy (G_f). Furthermore, boxplot analyses were conducted to examine the impact of traffic level, aggregate size, and aggregate type on the performance test results. Finally, preliminary performance test criteria for WisDOT mixes were suggested based on the database analysis results.

- **BMD Optimization Experiment.** Numerous mix design modification strategies were investigated to determine their effectiveness in improving performance test results. Strategies included increasing asphalt contents, removing RAS, adding a recycling agent, and using a softer virgin binder to improve mixture cracking resistance; using a higher MSCR binder grade to improve rutting resistance; and adding a liquid anti-strip to reduce moisture susceptibility. In a few cases, fixing one performance issue created another performance issue in the mix design modification process, which highlights the need for using multiple mixture performance tests to ensure a balance between mixture rutting, cracking, and moisture damage resistance.
- **Cost Analysis.** A simple cost analysis of the mix design modifications to improve five poorly performing mixes indicates that materials cost could increase by approximately 8 to 22% to meet the proposed criteria. Using a rejuvenator and increasing the asphalt content were both effective in improving the IDEAL-CT results and could be alternative economic strategies for adjusting mix designs. However, in one case, eliminating RAS was found to be less cost effective than increasing the asphalt content for improving mixture cracking resistance. For asphalt contractors to remain competitive in a low-bid environment, they will need to explore different mix design modification strategies so that they can determine the most cost-effective options for their materials.

Based on test results and findings of this project, it is recommended for WisDOT to continue to use the current specification with the regressed air voids approach for the design of Low Traffic (LT) mixes. On the other hand, the Performance-modified Volumetric Design approach is recommended for WisDOT to design Medium Traffic (MT), High Traffic (HT), and stone matrix asphalt (SMA) mixes. This BMD approach will help ensure satisfactory mixture rutting and cracking resistance while providing mix designers with some innovation potential to meet performance test requirements. Suggested modifications to the WisDOT specification are provided to facilitate the implementation of BMD for MT, HT, and SMA mixes. Finally, recommendations for future research and implementation activities are provided to further advance the implementation of BMD in Wisconsin.

ACKNOWLEDGEMENT

The authors acknowledge the support from the Project Oversight Committee (POC) in refining the experimental plan, identifying the materials and mix designs to be used in this study, coordinating the collection and delivery of all the materials, recommending mix design subject matter experts, evaluating project progress, and reviewing and providing recommendations to improve this report. The authors also acknowledge the support provided by Wisconsin contractors with the fabrication of mixture specimens for performance testing needed for the benchmarking experiment.

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1. INTRODUCTION

Currently in the United States, most asphalt mixtures are designed using the Superpave system where proportioning of mixture components relies largely on volumetric requirements. Early Superpave implementation focused on improving mixture rutting resistance by using higher quality aggregates, polymer modification of asphalt binders, and higher compactive efforts. Most highway agencies now report that rutting problems have been virtually eliminated. However, durability-related distress such as cracking and raveling primarily control the service lives of asphalt pavements. To address the durability concern, the Wisconsin Department of Transportation (WisDOT) implemented the regressed air voids approach, which was supported by the findings of WHRP project 0092-16-06 (West et al., 2018). Although the regressed air voids approach is expected to improve mixture cracking resistance without compromising rutting resistance by increasing asphalt contents up to 0.4%, implementing performance tests for balanced mix design (BMD) may further improve the long-term performance of asphalt pavements in Wisconsin.

BMD is defined as a mix design procedure that uses performance tests on appropriately conditioned specimens to address multiple modes of distress while taking into consideration mix aging, traffic, climate, and location within the pavement structure. BMD typically includes two or more mixture performance tests such a rutting test and a cracking test to assess how well the mixture resists these distresses. Although there are numerous mixture performance tests to choose from, the most popular tests for BMD are the simple index tests such as the Hamburg Wheel Tracking Test (HWTT) for assessing rutting and moisture damage resistance, the IDEAL Cracking Test (IDEAL-CT) for assessing load-related cracking resistance, and the Disc-Shaped Compact Tension (DCT) Test used to assess resistance to low-temperature cracking. WisDOT has initially selected these three tests for BMD implementation. There are four BMD approaches described in AASHTO PP 105-20 for conducting asphalt mix designs: A) Volumetric design with performance verification, B) Volumetric design with performance optimization, C) Performance-modified volumetric design, and D) Performance design. Different from the Superpave mix design, BMD requires mix designers to check the performance-related properties of the end product instead of relying solely on the volumetric requirements. End-product testing allows mix designers to be more innovative with component materials and additives to design asphalt mixtures and provides agencies with a more reliable way of accepting mixtures for asphalt pavements.

In recent WHRP projects, researchers identified mix design factors sensitive to performance properties and recommended test procedures for evaluation of mixture cracking and rutting resistance (Bahia et al., 2016; Bonaquist, 2016; West et al., 2018). As WisDOT works toward a draft BMD specification for mix design approval and eventually for mixture acceptance on paving projects, further information is needed regarding how current Wisconsin asphalt mixtures perform in the BMD tests and the most economical ways to improve mixes that are lacking in resistance to one or more of the distresses.

Therefore, this research project focused on the development of a preliminary performance-based specification that considers practical constraints in the mix design process, such as cost, available materials, construction practices, and others. The goal of the preliminary specification is to optimize the quality of asphalt paving mixtures in order to improve the service lives of asphalt pavements using the most economical approaches.

1.1 Project Objectives

The overall objective of this research was to assess and test performance-based methodologies with the intent of developing a preliminary implementable BMD specification for WisDOT projects. The specification was envisioned to consider multiple factors in the decision-making process of asphalt mix design, including economics, availability of materials, construction considerations, and additives, among others. One specific question that the research sought to address is how to prioritize these factors in the BMD process.

To accomplish the project objective, seven tasks were conducted:

Task 1. Synthesis of existing research and review of state specifications on BMD. This task required a detailed literature review synthetizing research studies and specifications using BMD. This synthesis was delivered by the research team on April 15, 2020. A condensed and revised version of this synthesis is provided in Chapter 1 of this report.

Task 2: Interview HMA designers to gather their insights on BMD implementation and specification limits. In this task, seven experienced Wisconsin mix designers were interviewed about their expectations and concerns of a BMD specification. A summary of the survey responses was submitted to the POC on April 15, 2020 and is included in Appendix A of this report.

Task 3. Develop pseudo-performance BMD criteria by benchmarking current WisDOT mix designs and conduct a BMD workshop in Wisconsin. The preliminary recommendations from this task were presented to the POC on February 7, 2020. The final recommendations are presented in Chapter 2 of this report. In addition, a BMD workshop was conducted in Wisconsin by Randy West and Fan Yin on December 4-5, 2019.

Task 4. Modify existing WisDOT mix designs to meet proposed BMD criteria. The preliminary recommendations from this task were presented to the POC on December 17, 2020. A few additional tests were completed in early 2021. The final results are presented in Chapter 3 of this report.

Task 5. Conduct an economic analysis of alternative BMD design modifications. Chapter 4 of this report discusses the economic analysis of test results obtained from the BMD optimization experiment.

Task 6. *Modify the WisDOT specification and propose performance testing thresholds to implement BMD.* Chapter 5 of this report provides suggested modifications to the WisDOT specifications for the implementation of BMD for MT, HT, and SMA mixes.

Task 7. Final Report. This task includes this final report documenting the findings of the study and project closeout activities that will take place by the end of April 2021.

1.2 Background

1.2.1 BMD Definition and Approaches

In September 2015, the former Federal Highway Administration (FHWA) Expert Task Group (ETG) on Mixtures and Construction formed a Balanced Mix Design Task Force, which consisted of asphalt researchers, practitioners, and pavement engineers from federal and state highway agencies, asphalt contractors, consultants, and academic and research institutions. The task force defined BMD as “asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate, and location within the pavement structure.”

BMD infers that the mixture is designed to achieve an optimal balance between rutting resistance and cracking resistance using appropriately selected mixture performance tests rather than relying solely on volumetric guidelines. Figure 1 through Figure 4 provide graphical illustrations of the four BMD approaches described in AASHTO PP 105-20. The major differences among these approaches are the degree of strictness on meeting existing volumetric criteria and the potential for innovation to meet the performance criteria. Each BMD approach is discussed in detail as follows.

A) Volumetric Design with Performance Verification, shown in Figure 1. This approach starts with the current volumetric mix design method (i.e., Superpave, Marshall, or Hveem) for determining an optimum binder content (OBC) that meets all the existing volumetric requirements. Alternatively, an existing agency-approved mix design can be used. The mix design at OBC is then tested with the selected mixture rutting and cracking tests. If the mix design fails the rutting and/or cracking test criteria, the entire mix design process is repeated using different materials (e.g., aggregates, asphalt binders, recycled materials, and additives) or mix proportions until all the volumetric, rutting, and cracking criteria are satisfied. After passing the rutting and cracking tests, the mix design is evaluated with the selected moisture damage test. If the design passes the moisture test criterion, the job mix formula is established for production. Otherwise, anti-strip agents such as liquid anti-strip (LAS) additives or hydrated lime need to be added and the modified mix is re-evaluated using the same moisture damage test until a passing result is obtained. If a LAS additive is used, it may be necessary to also repeat the rutting test on the modified mix for compliance verification due to the concern that some LAS additives can soften the asphalt binder and increase the rutting potential of asphalt mixtures. Alternatively, changing the asphalt binder source or aggregate type could also improve the moisture damage test result. However, these modifications are not preferred because they would require the mix to be redesigned to maintain compliance with all of the volumetric and performance criteria. This approach requires full compliance with the existing volumetric requirements and additional performance requirements and thus, is the most conservative approach with the lowest innovation potential.

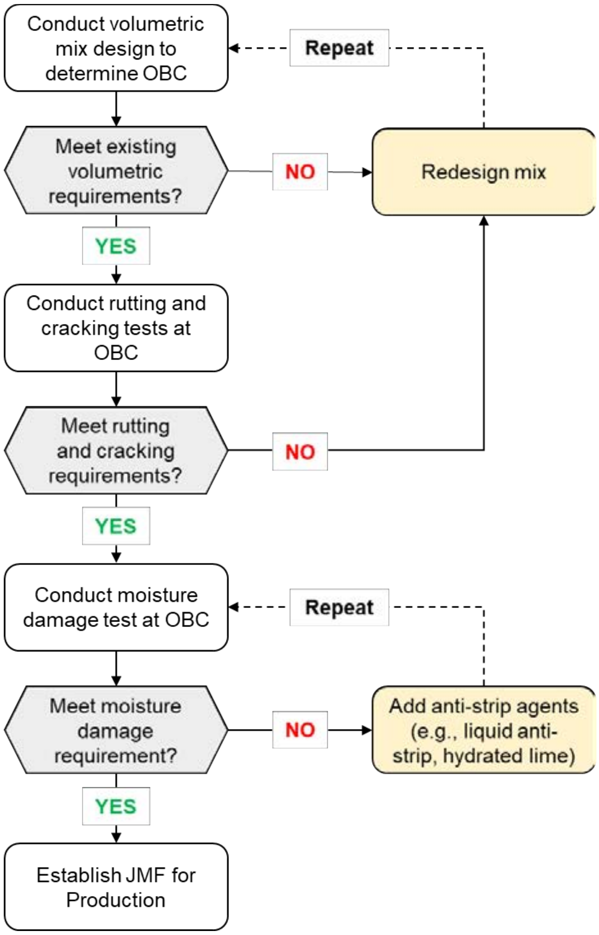

Figure 1. Graphical Illustration of the Volumetric Design with Performance Verification Approach

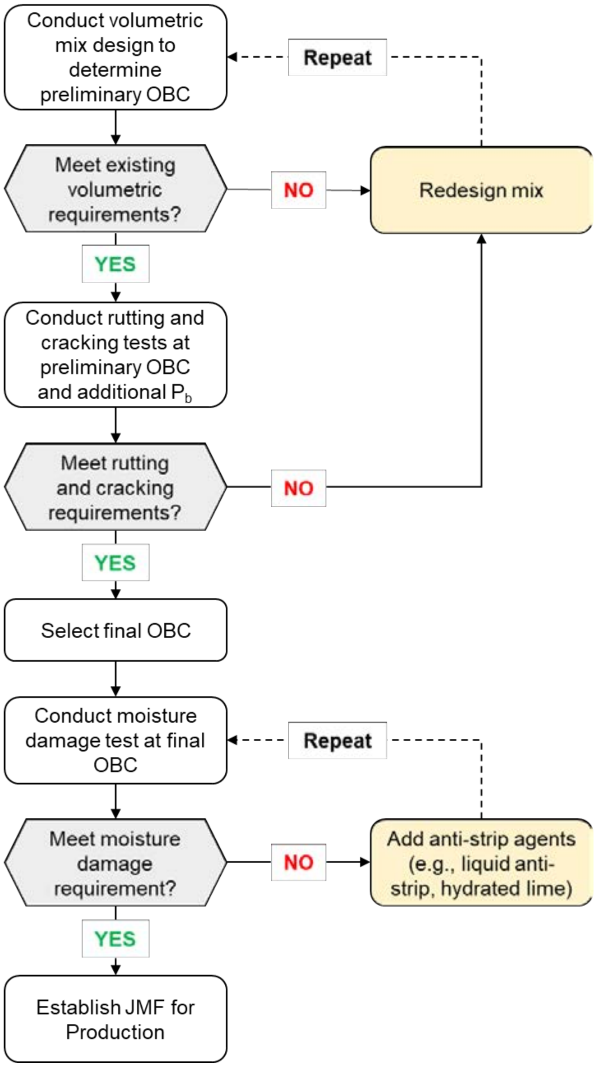

Figure 2. Graphical Illustration of the Volumetric Design with Performance Optimization Approach

B) Volumetric Design with Performance Optimization, shown in Figure 2. This approach is an expanded version of Approach A. It also starts with the current volumetric mix design method (i.e., Superpave, Marshall, or Hveem) for determining a preliminary OBC that meets all the existing volumetric requirements. Alternatively, an existing agency-approved mix design can be used. The mix design is then tested with the selected mixture rutting and cracking tests at the preliminary OBC and two or more additional binder contents at intervals of ± 0.3 to 0.5% that bracket the preliminary OBC. Then, a binder content (not necessarily the lowest content) that satisfies both the rutting and cracking test criteria is selected as the final OBC. In cases where a passing binder content is not achieved, the entire mix design process is repeated using different mix components or proportions (e.g., aggregates, asphalt binders, recycled materials, and additives) until both the rutting and cracking criteria are satisfied. After the final OBC is selected, the mix design is then evaluated with the selected moisture damage test. If the design passes the moisture test criterion, the job mix formula is established for production. Otherwise, anti-strip agents need to be added and the modified mix is re-evaluated using the same moisture damage test until the criterion is satisfied. Additional rutting and cracking tests could also be conducted on the modified mix for performance verification purposes. This approach requires full compliance with the existing volumetric requirements at the preliminary OBC but allows moderate changes in asphalt binder content for performance optimization based on mixture performance test results. Although this approach is slightly more flexible than Approach B, it is still considered conservative with limited innovation potential.

C) Performance-Modified Volumetric Design, shown in Figure 3. This approach starts with the current volumetric mix design method (i.e., Superpave, Marshall, or Hveem) to establish an initial aggregate structure and binder content or an existing agency-approved mix design. The initial design is then tested with the selected rutting and cracking tests. Test results are used to decide how to adjust the mix using other binder contents, component materials, or proportions until both the rutting and cracking criteria are satisfied. Then, the mix design is evaluated with the selected moisture damage test. If the design passes the moisture test criterion, certain volumetric properties are measured and verified for compliance with the agency's relaxed requirements prior to establishing the job mix formula. Otherwise, anti-strip agents need to be added and the modified mix is reevaluated using the same moisture damage test until the criterion is satisfied. Additional rutting and cracking tests should also be conducted on the modified mix for performance verification purposes. This approach allows some of the volumetric requirements to be relaxed or eliminated provided that the performance criteria are satisfied. The mix design modifications that can be used in this approach are not limited to changes in asphalt binder content. Therefore, it is less conservative than Approach A and Approach B and provides a medium degree of innovation potential.

D) Performance Design, shown in Figure 4. This approach starts with an existing agency-approved mix design or trial gradations, recycled asphalt materials contents, and virgin binder grade. The initial mix design or mix trials are then tested with the selected rutting and cracking tests at three or more binder contents at intervals of 0.3 to 0.5%. A binder content (not necessarily the lowest content) that satisfies both the rutting and cracking criteria is selected as the OBC. In cases where a passing mixture is not achieved, the initial mix design needs to be adjusted using different mix components or proportions until both the rutting and cracking criteria are satisfied. Then, the mix design is evaluated with the selected moisture damage test. If the design passes the moisture test criterion, the job mix design is established. Otherwise, anti-strip agents need to be added and the modified mix is re-evaluated using the same moisture damage test until the criterion is satisfied. Additional rutting and cracking tests should also be conducted on the modified mix for performance verification purposes. This approach has no requirements for volumetric properties and relies solely on mixture performance test results for mix design optimization, and thus, is considered the least conservative approach with the highest degree of innovation potential.

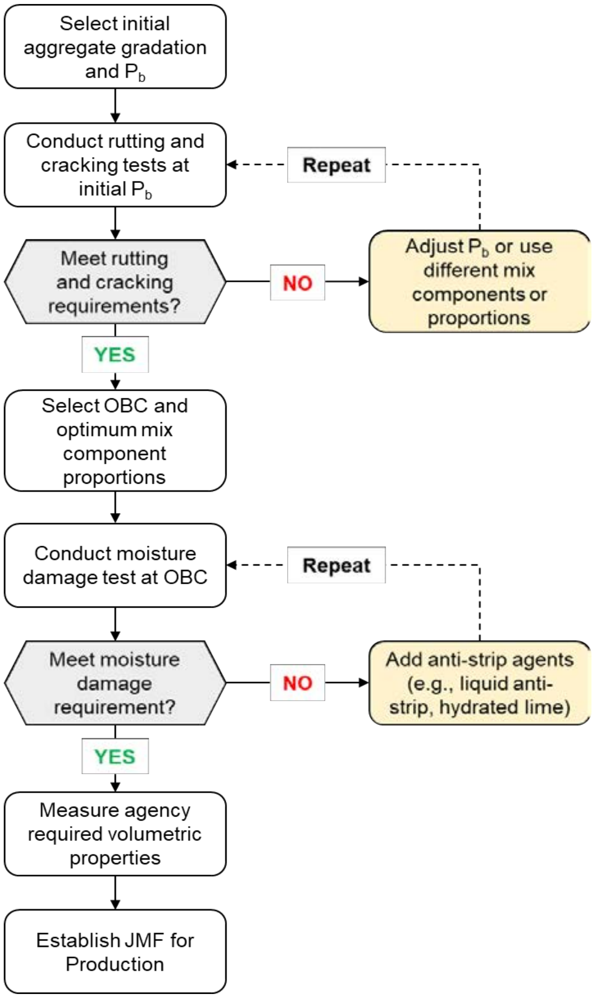

Figure 3. Graphical Illustration of the Performance-Modified Volumetric Design Approach

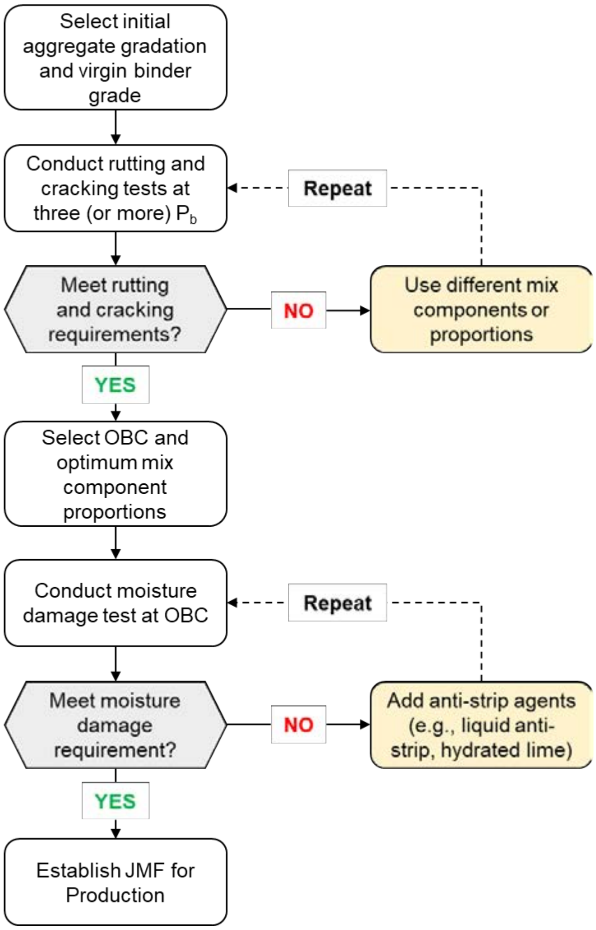

Figure 4. Graphical Illustration of the Performance Design Approach

1.2.2 BMD State-of-the-Practice

Figure 5 presents a U.S. map showing 11 state highway agencies (SHAs) that have developed either a draft, provisional, or standard BMD specification. This information was collected from a survey of SHAs and the asphalt pavement industry conducted by NCAT in May 2020 and information may not be completely up to date. Among the 11 states identified as having a BMD specification, Illinois, Louisiana, New Jersey, Texas, and Vermont use Approach A: Volumetric Design with Performance Verification; California, Missouri, and Oklahoma currently use Approach C: Performance-Modified Volumetric Design; Alabama and Tennessee are exploring Approach D: Performance Design; while Virginia allows both Approach A and Approach D. No states have yet to move forward with Approach B: Volumetric Design with Performance Optimization.

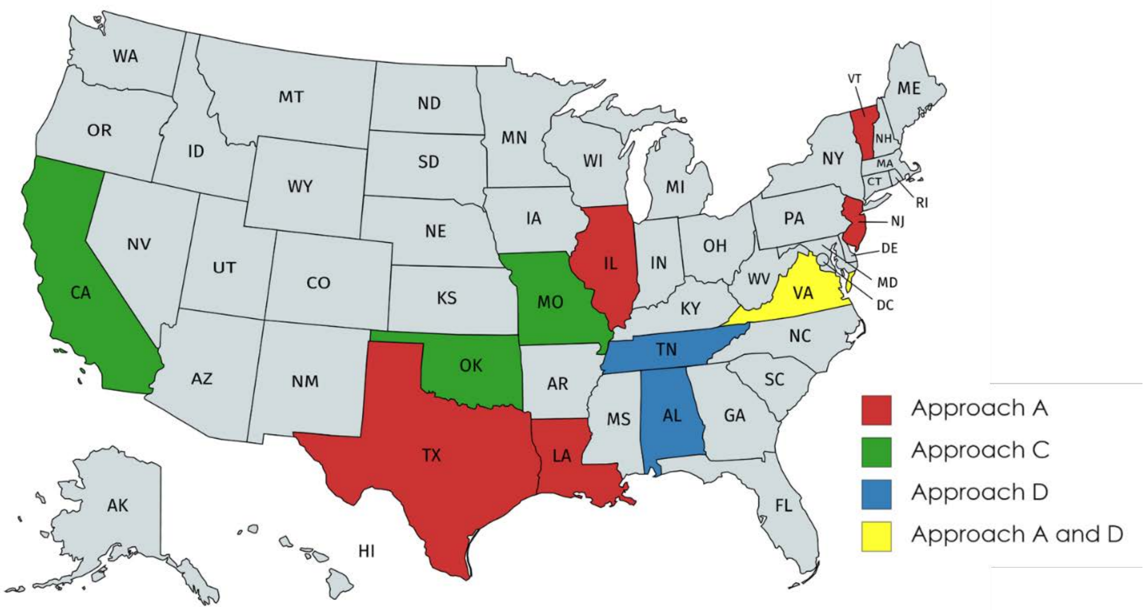

Figure 5. U.S. Map of SHAs with Draft, Provisional, or Standard BMD Specifications (Yin and West, 2021)

Table 1 provides additional information regarding the state-of-the-practice on the implementation of BMD for the 11 states in Figure 5, which includes the applicable mixture type, selected rutting and cracking tests, and use of performance testing for production acceptance. Detailed discussions about the BMD specifications of individual SHAs can be found elsewhere (Yin and West, 2021).

Table 1. Summary of State-of-the-Practice on BMD Implementation (Yin and West, 2021)

BMD Approach	State	Applicable Mixture Type	Rutting Test	Cracking Test	Performance Testing for Production Acceptance?
Approach A	Illinois	High ESAL mixtures	HWTT	I-FIT	Yes, HWTT for "Pass/Fail"
	Louisiana	Wearing and binder course mixtures	HWTT	SCB-Jc	Yes, "Pass/Fail"
	New Jersey	Specialty mixtures	APA	OT, BBF	Yes, "Pass/Fail" or Pay Adjustment
	Texas	Surface mixtures	HWTT	OT, IDEAL-CT	Yes, "Pass/Fail"
	Vermont	Superpave Type IVS mixtures	HWTT	I-FIT	Yes, PWL
Approach A and D	Virginia	Surface mixtures	APA	Cantabro, IDEAL-CT	Yes, "Pass/Fail"
Approach C	California	Long-life pavement mixtures	FN, HWTT	BBF, I-FIT	Yes, HWTT for "Pass/Fail"
	Missouri	Mainline pavement mixtures	HWTT	I-FIT, IDEAL-CT	Yes, HWTT for "Pass/Fail", I-FIT & IDEAL-CT for Pay Adjustment
	Oklahoma	Superpave mixtures	HWTT	IDEAL-CT	No
Approach D	Alabama	Superpave mixtures	HT-IDT	AL-CT	Yes, "Pass/Fail"
	Tennessee	All mixtures	HWTT	IDEAL-CT	To be determined

1.2.3 State Research Projects on BMD

In addition to states that have implemented a BMD approach, a number of research organizations and SHAs have completed or are currently conducting research to either explore or adopt cracking tests and BMD approaches. These states are highlighted in Figure 6. Several selected research projects are briefly discussed as follows.

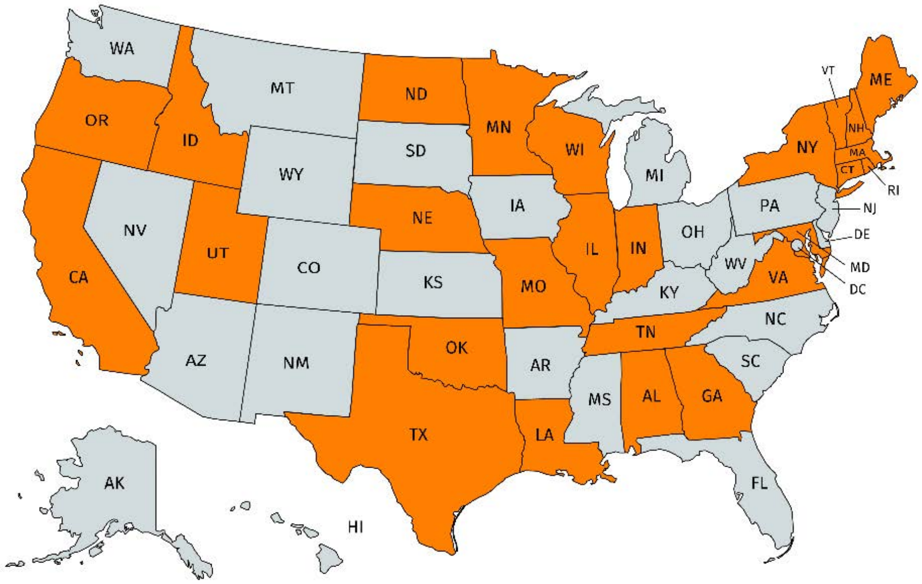

Figure 6. U.S. Map of SHAs with Completed or Ongoing Research Projects on BMD

Arkansas. A study was sponsored by Arkansas DOT to develop or adapt a cracking test to be recommended for implementation along with the APA rutting test for BMD. The study compared laboratory cracking results using I-FIT and IDEAL-CT to field performance for Arkansas surface mixes with a NMAS of 9.5 and/or 12.5 mm. CT_{Index} and FI values ranked the mixtures in the same manner, thus IDEAL-CT was recommended for assessing cracking resistance during asphalt mixture design due to its simplicity. Based on the data obtained in this study, a minimum CT_{Index} of 50 was recommended for Arkansas (Hall et al., 2019).

Minnesota. Newcomb and Zhou (2018) conducted a research study for the Minnesota Department of Transportation to develop a framework for BMD. The study evaluated four asphalt mixtures from Minnesota projects using three cracking tests (DCT, I-FIT, and IDEAL-CT) and one rutting test (HWTT). The performance tests and the BMD procedure followed were able to capture the impact of asphalt content on cracking and rutting resistance. Among the cracking tests, there was fairly good agreement in terms of asphalt content with a small deviation from volumetric asphalt content in most cases. Since the criteria selected for the different performance tests corresponded to those proposed by the test developers or other agencies, the researchers recommended that these criteria should be further refined or validated in future research to account for different applications based on climate, lift thickness, traffic level, and location within the pavement structure.

Oklahoma. A study sponsored by the Oklahoma DOT (ODOT) evaluated mixtures to select a cracking test for use in BMD. The study evaluated I-FIT test results from 31 existing mixes and IDEAL-CT test results from nine mixes. A weak correlation was found between FI and CT_{Index}. The results indicated that the CT_{Index} equivalent to an FI of 8 could be larger than 100, compared to the typical reported value of 80. The researchers recommended that ODOT consider adopting

IDEAL-CT due to its simplicity and that all mix designs submitted for use on ODOT projects be tested to establish CT_{Index} criteria requirements (Cross and Li, 2019).

Utah. A project sponsored by the Utah Department of Transportation is currently underway to evaluate the ability of IDEAL-CT to determine the cracking potential of asphalt mixtures. The project will compare IDEAL-CT results with previous I-FIT results using the same materials in terms of correlation to field performance, repeatability, and simplicity. The project objective is to select the simplest, most cost effective, and most reliable cracking test to facilitate adoption by state agencies (Romero, 2019).

Wisconsin. The Wisconsin DOT has conducted pilot studies to evaluate the use of performance tests for mixtures containing more than 25% recycled materials (Paye, 2015). For these pilot projects, WisDOT required the HWTT to evaluate moisture and rutting resistance, the DCT test for low temperature cracking resistance, and the SCB- J_c test for fatigue cracking resistance. At the local level, the City of Janesville has incorporated additional performance criteria for mix design verification and acceptance based on these same tests (City of Janesville, 2020). According to their current specifications, asphalt mix designs must meet the performance requirements for the DCT, I-FIT, and HWTT.

Another research project sponsored by WisDOT evaluated the regressed air voids approach for BMD. The project determined the impact of increasing asphalt contents using air voids regression on HWTT, DCT, and I-FIT results. The experimental plan included mixes designed for low, medium, and high traffic levels with various RAP and RAS contents. Test results indicated that the regressed air voids concept improved mixture cracking resistance without compromising the rutting resistance of asphalt mixes (West et al., 2018).

1.2.4 Asphalt Mixture Performance Tests

Over the past few decades, numerous performance tests have been developed by asphalt researchers to evaluate the rutting resistance, cracking resistance, and moisture susceptibility of asphalt mixtures. Considering the different mechanisms involved in crack initiation and propagation, mixture cracking tests can be further categorized into tests for thermal cracking, reflection cracking, bottom-up cracking, and top-down cracking. Table 2 provides a list of mixture performance tests that are commonly used in asphalt research and are being considered by state highway agencies. A one-page summary for most of the mixture performance tests listed in the table can be found in the NCHRP Project 20-07/Task 406 final report (West et al., 2018) and NAPA Information Series 143, *Balanced Mix Design Resource Guide* (Yin and West, 2021). Some of these performance tests are better suited for routine use in mix design and quality assurance testing, while others are more focused on characterizing the fundamental properties of asphalt mixtures to be used in modeling pavement responses and predicting pavement damage.

As part of NCHRP Project 20-07/Task 406, an online survey was conducted where the participating SHAs and asphalt contractors were asked to select their most preferred performance tests for each mode of distress. Their responses are summarized below:

- Rutting: HWTT, APA
- Bottom-up cracking: I-FIT, BBF
- Top-down cracking: I-FIT, Asphalt Mixture Performance Tester (AMPT) cyclic fatigue
- Thermal cracking: DCT, low-temperature SCB
- Reflection cracking: OT, I-FIT
- Moisture damage: HWTT, TSR

Note that the IDEAL-CT, IDEAL-RT, and AMPT SSR tests were still under development when the survey was conducted in 2017; thus, these tests were not included in the survey.

Since the completion of NCHRP Project 20-07/Task 406, a few SHAs have implemented a rutting and/or cracking test for asphalt mix design. Figure 7 through Figure 9 summarize the selection of mixture performance tests by SHAs as of March 2020. As shown in Figure 7, HWTT (14 states) and APA (10 states) are the two most popular rutting tests, followed by the Hveem stability test (2 states), and FN (1 state). Figure 8 shows that BBF (4 states), IDEAL-CT (3 states), I-FIT (3 states), and DCT (3 states) are currently the most popular cracking tests, followed by OT (2 states), SCB-LA (1 state), and Cantabro (1 test). The selection of moisture damage tests is presented in Figure 9, with TSR being used by 36 states, HWTT by seven states, the immersion compression test by two states, the retained stability test by one state, and the asphalt film retention test by one state.

Table 2. List of Commonly Used Asphalt Mixture Performance Tests

Mixture Property	Laboratory Test	Test Standard	Test Parameter(s)
Rutting Resistance	Asphalt Pavement Analyzer (APA)	AASHTO T 340-10	Rut Depth
	Flow Number (FN)	AASHTO T 378-17	Flow Number
	Hamburg Wheel Tracking Test (HWTT)	AASHTO T 324-19	Rut Depth
	AMPT Stress Sweep Rutting (SSR)	AASHTO TP 134-19	Rutting Shift Model, Index Parameter *RSI*
	High Temperature Indirect Tension (HT-IDT)	N/A	Indirect Tension Strength
	Rapid Shear Rutting Test (IDEAL-RT)	N/A	Rutting Tolerance Index (RT_{Index})
Cracking Resistance /Durability	AMPT Cyclic Fatigue Test	AASHTO TP 107-14 AASHTO TP 133-19	Damage Characteristic Curve & Fatigue Model, Index Parameter S_{app}
	Disk-Shaped Compact Tension (DCT) Test	ASTM D7313-13	Fracture Energy
	Flexural Bending Beam Fatigue (BBF)Test	AASHTO T 321-17 ASTM D8273-18	Cycles to Failure Fatigue Equation
	Illinois Flexibility Index Test (I-FIT)	AASHTO TP 124-18	Flexibility Index (FI)
	Indirect Tensile Creep & Strength Test	AASHTO T 322-07	Creep Compliance & Tensile Strength
	Indirect Tensile Cracking Test (IDEAL-CT)	ASTM D 8225-19	Cracking Tolerance Index (CT_{Index})
	Indirect Tensile Energy Ratio (ER) Test	N/A	Dissipated Creep Strain Energy & Energy Ratio
	Intermediate-Temperature Semi-Circular Bend (SCB-LA)	LaDOTD TR 330-14 ASTM D8044-16	Strain Energy Release Rate
	Low-Temperature Semi-Circular Bend Test	AASHTO TP 105-13	Fracture Energy
	Texas Overlay (OT) Test	TxDOT Tex-248-F NJDOT B-10	Cycles to Failure & Fracture Properties
	Thermal Stress Restrained Specimen Test (TSRST)	BS EN12697-4	Fracture Temperature & Fracture Strength
	Cantabro Abrasion Loss	AASHTO TP 108-14	Mass Loss
Moisture Resistance	Hamburg Wheel Tracking Test (HWTT)	AASHTO T 324-19	Rut Depth & Stripping Inflection Point
	Moisture Induced Stress Tester (MIST)	ASTM D7870-13	Changes in G_{mb} & Visual Observations of Stripping
	Tensile Strength Ratio (TSR)	AASHTO T 283-14	Tensile Strength Ratio & Wet IDT Strength

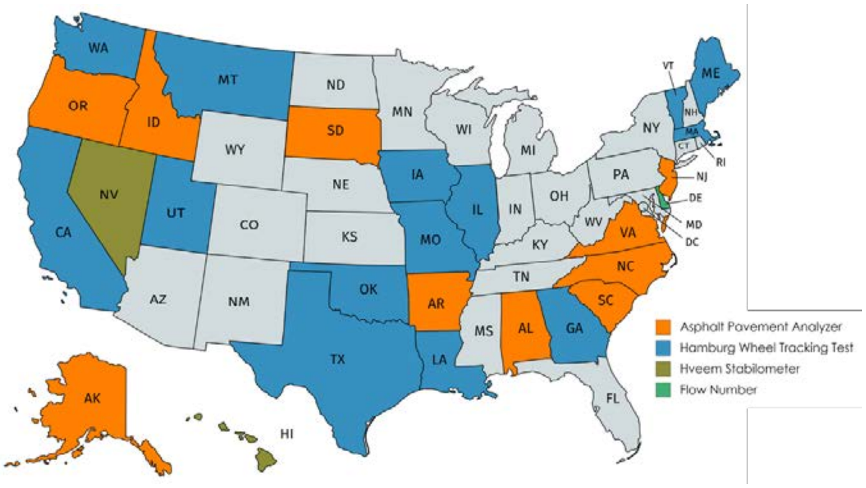

Figure 7. U.S. Map of Rutting Tests by State Highway Agencies (as of March 2020)

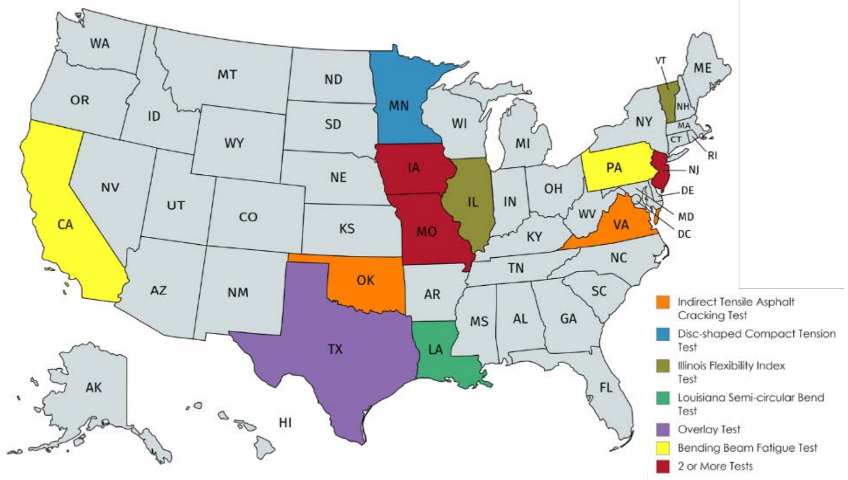

Figure 8. U.S. Map of Cracking Tests by State Highway Agencies (as of March 2020)

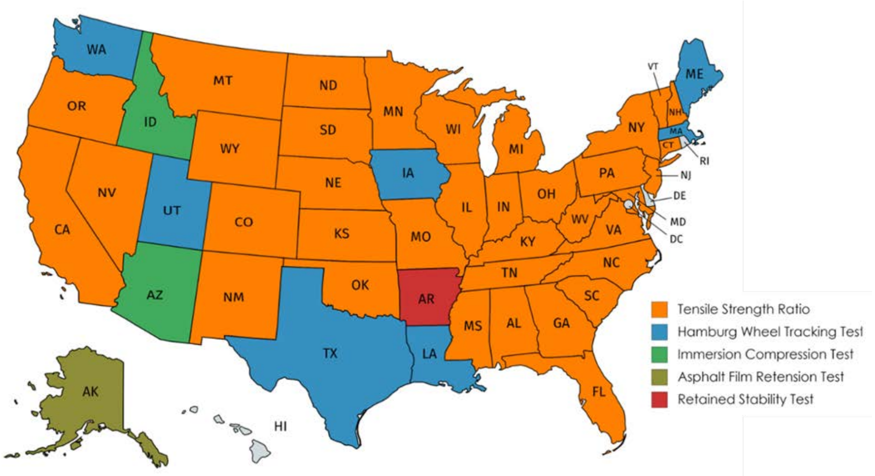

Figure 9. U.S. Map of Moisture Damage Tests by State Highway Agencies (as of March 2020)

1.2.5 Impact of Mix Design Variables on Mixture Performance

This section discusses the effects of common mix design variables on mixture performance test results as guidance on mix design modifications for BMD. For each mix design variable discussed here, examples of test results for before-versus-after design modification comparisons can be found in NAPA Information Series 142, *Balanced Mix Design Resource Guide* (Yin and West, 2021). In addition to performance test results, material availability and costs should be considered when modifying mix designs. In a low-bid environment, mix designers will likely explore the most cost-effective BMD optimization method to be competitive while meeting the agency's mixture performance test requirements.

Asphalt binder content. Asphalt binder content is arguably the most significant mix design variable affecting the performance test results of asphalt mixtures. In general, increasing the asphalt binder content improves the cracking resistance but reduces the rutting resistance of asphalt mixtures. Increasing asphalt binder content is also expected to have a positive effect on resistance to moisture damage due to better aggregate coating and reduced permeability associated with better in-place density. Finally, it should be noted that changing the asphalt binder content without adjusting the aggregate gradation and/or compaction effort will also affect the mixture's volumetric properties.

Virgin binder grade and source. There are two factors relevant to asphalt binder that affect the performance test results of asphalt mixtures: the volume and the quality of asphalt binder. The former is governed by the total binder content and effective binder content (or the volume of effective binder, V_{be}), while the latter depends on the grade and source of virgin binder as well as the qualities of recycled binders and interactions with asphalt additives, if used. In general, stiffer asphalt binders are expected to yield mixtures with improved rutting resistance but reduced cracking resistance, although there are exceptions such as polymer modified asphalt (PMA) binders. Therefore, mix designers can consider using a stiffer virgin binder to improve the rutting test results or a softer binder to improve the cracking test results for BMD. In addition to binder grade, the source of virgin binder may also affect the mixture performance test results. Asphalt binders with the same PG grade are not necessarily of the same quality due to differences in the crude source and refining process. Therefore, additional binder parameters other than those specified in the Superpave PG specification (such as the Delta Tc and Glover-Rowe parameter) should be considered by the mix designer when selecting a virgin binder for BMD. Changing the virgin binder grade or source is not likely to have a significant impact on the volumetric properties of asphalt mixtures provided that the mixing and compaction temperatures are appropriately adjusted to account for the differences in binder viscosity.

Polymer modification. The asphalt pavement industry has a long history of using polymer modified asphalt to improve the performance and service life of asphalt pavements. Extensive research efforts have confirmed the benefit of polymer modification in improving the rutting resistance of asphalt mixtures due to increased binder stiffness and in some cases, improved binder elasticity. Furthermore, a vast number of field projects have demonstrated improved fatigue cracking performance of pavements containing polymer modified asphalt compared to pavements with unmodified asphalt (Asphalt Institute, 2005). However, several recent studies have shown that the use of PMA does not always yield better results in some intermediate-temperature cracking tests, especially those requiring the analysis of post-peak load versus displacement data (Hanz, 2017; Fort, 2018). These test results do not agree with many existing field cracking performance data and thus, warrant further investigation (National Road Research Alliance, 2021). Polymer modification is not likely to affect the volumetric properties of asphalt mixtures provided that the mixing and compaction temperatures are adjusted to accommodate the differences in viscosity of asphalt binders.

Aggregate gradation. Aggregate gradation plays a significant role in volumetric mix design by affecting the skeleton structure of the mixture and the amount of asphalt binder needed to achieve a target air voids content at N_{design}. It has been widely acknowledged that better aggregate interlock contributes to improved rutting resistance of asphalt mixtures due to enhanced load-carrying capability and shear strength. However, the impact of aggregate gradation on the cracking resistance of asphalt mixtures has yet to be evaluated in a systematic manner. Investigating the impact of gradation on cracking resistance is complicated by the fact that changing aggregate gradation will also change volumetric properties and optimum asphalt binder content, which therefore confounds the analysis. However, when BMD can allow certain volumetric properties to be relaxed or eliminated, it provides an opportunity to assess the impact of aggregate gradation as an independent mix design variable on the mixture performance test results. Unfortunately, very limited information is currently available on this matter.

Recycled asphalt material content. Recycled asphalt materials including reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS) contain heavily aged asphalt binders that are stiffer and more brittle than virgin binders. Therefore, increasing the RAP/RAS content generally improves the stiffness and rutting resistance of asphalt mixtures but makes them more susceptible to fatigue cracking and low-temperature cracking. Changing the RAP/RAS content for a mix design will also affect mixture volumetrics due to the associated changes in asphalt binder content and aggregate gradation.

Recycling agents. Recycling agents are organic materials with chemical and physical characteristics selected to restore aged binder to desired specifications. Recycling agents can be grouped into two categories: softening agents and rejuvenators (Asphalt Institute, 1986; Willis and Tran, 2015). Softening agents are mainly used to reduce the viscosity of virgin and recycled binder blends, while rejuvenators may reduce the viscosity but are primarily intended to partially restore the chemical balance and rheological properties of binder blends (Epps Martin et al., 2019; Hand and Epps Martin, 2020). Over the past few years, there has been increasing use of recycling agents for the design and production of asphalt mixtures containing high RAP and/or RAS contents. The addition of recycling agents is expected to improve the cracking resistance but reduce the rutting resistance of asphalt mixtures. However, the effectiveness of recycling agents on mixture performance test results varies significantly depending on the type of recycling agent, RAP/RAS source, source of virgin binder, and compatibility between recycling agent, virgin binder, and recycled binder, among others. The impact of recycling agents on the volumetrics and moisture susceptibility of asphalt mixtures has not been investigated in a comprehensive manner and warrants further research.

Anti-strip agents. LAS additives and hydrated lime are the two most commonly used anti-strip agents for improving the moisture resistance of asphalt mixtures. LAS additives are mainly surface-active agents that are designed to decrease the surface tension between asphalt binder and aggregate surface, thereby allowing aggregate to be more easily wetted by asphalt binder. Adding LAS additives increases the strength of asphalt-aggregate adhesion and reduces its susceptibility to moisture damage. The effectiveness of LAS additives in improving moisture resistance, however, varies greatly from product to product. Overdosing LAS additives could soften the asphalt binders, possibly making the resultant mixtures more susceptible to rutting but more resistant to cracking. Hydrated lime is an effective anti-strip agent due to its highly alkaline properties that neutralize organic acids in asphalt binder and increase the base surface energy of aggregates, which consequently reduces the moisture and stripping potential of asphalt mixtures (Kennedy et al., 1983; Little and Epps, 2001). Previous research has also indicated that hydrated lime provides asphalt mixtures with additional performance benefits such as improved rutting resistance, low-temperature fracture toughness, and aging resistance (Sebaaly et al., 2006).

2. DEVELOPMENT OF PRELIMINARY PERFORMANCE TEST CRITERIA

This chapter provides the experimental plan, test results, and data analysis of the benchmarking experiment. The objective of this experiment was to test the existing WisDOT-approved mix designs with the selected performance tests to determine the distribution of test results. Based on WisDOT's previous experience with mixture performance testing, the Hamburg Wheel Tracking Test (HWTT), Indirect Tensile Asphalt Cracking Test (IDEAL-CT), and Disc-shaped Compact Tension (DCT) Test were selected for BMD. HWTT was used to evaluate the rutting resistance and moisture susceptibility of asphalt mixtures, while IDEAL-CT and DCT were used for the evaluation of intermediate-temperature and low-temperature cracking resistance, respectively.

The benchmarking experiment focused on the evaluation of lab-mixed, lab-compacted (LMLC) specimens for 18 existing mix designs with various mixture types, aggregate NMAS, binder grades, traffic levels, and aggregate types. For each mix design, the HWTT, IDEAL-CT, and DCT specimens were prepared by Wisconsin contractors following a step-by-step specimen fabrication procedure prepared by NCAT. The specimens were then shipped to the NCAT laboratory for performance testing. Upon completion of the experiment, a database of mixture performance test results was established. Data analysis was then conducted with test results to develop preliminary performance test criteria for WisDOT mixes for the implementation of BMD.

2.1 Experimental Plan

2.1.1 Mix Design Selection

The 18 mix designs selected by the POC for evaluation in the benchmarking experiment are summarized in Table 3. These mix designs included one SMA mix and seventeen Superpave dense-graded mixes. Thirteen out of the eighteen mix designs were 12.5mm NMAS mixes, and the rest were 9.5mm NMAS mixes. All of the mix designs except two used a PG 58S-28 unmodified binder while the two exceptions were a PG 58V-28 modified binder used in the SMA mix and a PG 52S-34 unmodified binder used in a 35% RAP mix. Among the seventeen Superpave dense-graded mixes, five were in the Low Traffic (LT) category with design traffic less than 2* million equivalent single axle loads (ESALs), nine in the Medium Traffic (MT) category with design traffic between 2* and 8 million ESALs, and three in the High Traffic (HT) category with design traffic over 8 million ESALs. The corresponding design gyration (N_{design}) of LT, MT, and HT mixes is 40, 75, and 100 gyrations, respectively. The mix designs included four primary aggregate types: gravel (six mixes), carbonate (eight mixes), granite (two mixes), and quartz (two mixes). Seventeen of the mixes contained RAS at between 10 and 35% of the mix while six of the mixes contained RAS at 2.0 to 3.4% of the mix. All the Superpave dense-graded mixes were designed with a regressed air voids of 3.0% while the SMA mix was designed with 4.5% air voids per WisDOT specifications.

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*The separation between WisDOT's low and medium traffic levels was later changed to 1 million ESALs.

Table 3. Summary of Mix Designs in the Benchmarking Experiment

Mix ID	Traffic Level	NMAS	Primary Aggregate Type	PG Grade	RAP (%)	RAS (%)	Air Voids (%)
A	SMA	12.5	Carbonate	58V-28	0	3	4.5
B	HT	12.5	Gravel	58S-28	10	0	3.0
C	HT	12.5	Carbonate	58S-28	16	0	3.0
D	HT	12.5	Carbonate	58S-28	15	0	3.0
E	MT	9.5	Gravel	58S-28	30	0	3.0
F	MT	9.5	Gravel	52S-34	35	0	3.0
G	MT	9.5	Carbonate	58S-28	31	0	3.0
H	MT	9.5	Carbonate	58S-28	30	0	3.0
I	MT	12.5	Granite	58S-28	14	2	3.0
J	MT	12.5	Gravel	58S-28	38	0	3.0
K	MT	12.5	Carbonate	58S-28	26	0	3.0
L	MT	12.5	Carbonate	58S-28	10.1	3.4	3.0
M	MT	12.5	Quartz	58S-28	18	3	3.0
N	LT	9.5	Gravel	58S-28	32	0	3.0
O	LT	12.5	Granite	58S-28	20	2	3.0
P	LT	12.5	Gravel	58S-28	29	0	3.0
Q	LT	12.5	Carbonate	58S-28	29	0	3.0
R	LT	12.5	Quartz	58S-28	21	3	3.0

2.1.2 Specimen Fabrication for Performance Testing

To reduce the inter-laboratory variability associated with specimen fabrication among the contractors and its resultant impact on the mixture performance test results, a step-by-step specimen fabrication procedure was prepared by NCAT and provided to the participating contractors in the benchmarking experiment. The procedure includes detailed instructions for determining trial weights for fabricating performance testing specimens with targeted height and air voids, as well as the short-term and long-term aging of the loose mixture prior to compaction. A copy of the NCAT specimen fabrication procedure is provided in Appendix B.

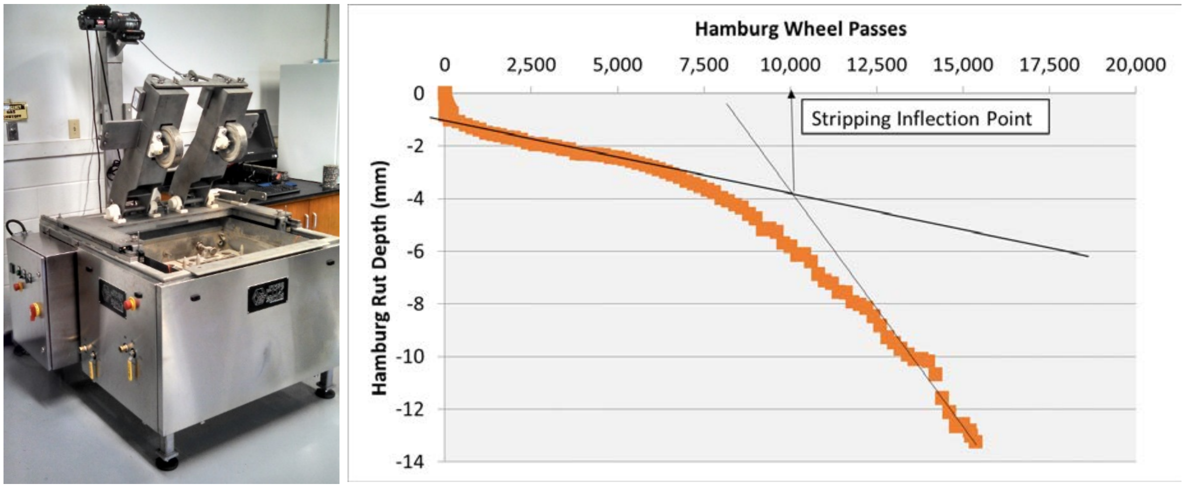
HWTT specimens were prepared at the short-term aging condition, while IDEAL-CT and DCT specimens were prepared after the long-term aging procedure often referred to as the “critical aging” procedure to consider the impact of asphalt aging on mixture cracking resistance. The short-term aging procedure used was loose mixture aging for four hours at 135°C per AASHTO R 30, Section 7.2. The long-term aging procedure corresponded to loose mixture aging for six hours at 135°C in addition to the four-hour short-term aging at 135°C. This procedure was recommended by Bahia et al. (2018) as the standard long-term aging procedure for Wisconsin mixes in WHRP project 17-04 and has also been used in the MnROAD Cracking Group Experiment study (Vrtis, 2020) and NRRA Mix Rejuvenator Test Sections (Phase II) study (Sias et al., 2020), among others. Compared to the short-term aging procedure, the long-term aging procedure requires aging of the loose mixture in a thinner layer (i.e., no more than ¾ to 1" thick) to increase the exposure to heat and oxygen for accelerated oxidation.

HWTT and IDEAL-CT specimens were compacted to 62 mm with a target air voids of 7.0 ± 0.5%. DCT specimens were compacted to 160 mm with a target air voids between 7.4 and 8.0%, which were further trimmed and cut at the NCAT laboratory for DCT testing. The goal was for the final trimmed DCT specimens to be close to 7.0% air voids. For each mix design included in the benchmarking experiment, a minimum of ten 62 mm tall specimens (for HWTT and IDEAL-CT) and four 160 mm tall specimens (for DCT) were provided by the Wisconsin contractor for performance testing at NCAT.

2.1.3 Mixture Performance Testing

<u>Hamburg Wheel Tracking Test (HWTT)</u>

The Hamburg Wheel Tracking Test device shown in Figure 10(a) was used to evaluate the rutting resistance and moisture susceptibility of asphalt mixtures in the study. HWTT testing was performed in accordance with AASHTO T 324-19 with the exception that a lower test temperature of 46°C was used per the request of the POC. Two replicates were tested per mix, with each replicate consisting of two trimmed specimens (four specimens total per mix). The specimens were originally compacted using an SGC to a diameter of 150 mm and a height of 62 mm. The specimen ends were then trimmed to fit in the HWTT molds for testing. The target air voids content of the HWTT specimens was 7.0 ± 0.5 percent.



(a) (b)

Figure 10. Hamburg Wheel Tracking Test (a) Device at the NCAT Laboratory, (b) Example Rut Depth Data

The specimens were tested under a 158 ± 1 pound wheel load for 10,000 cycles (20,000 passes) while submerged in a water bath maintained at 46°C. Rut depths were measured by a linear variable differential transformer (LVDT) throughout the test. After testing, the rut depth data were used to determine the point at which stripping occurred in the mixture under loading and to assess the relative rutting susceptibility of the mixture. Testing was terminated early in the event of severe rutting (i.e., greater than 12.5 mm rutting before reaching 20,000 passes). Figure 10(b) illustrates a typical data output from the HWTT device, which shows the progression of rut depth with number of wheel passes. Two tangents are evident from the curve: the steady-state rutting portion of the curve and the portion of the curve after stripping. The intersection of these two curve tangents defines the stripping inflection point (*SIP*) of the mixture.

The primary HWTT data analysis used in this study followed the method by Yin et al. (2014), which decomposes the HWTT curve into a steady-state (corrected) rut depth portion for the evaluation of rutting resistance and a post-stripping portion for the evaluation of moisture susceptibility, as illustrated in Figure 11. This method isolates the rut depth due to permanent deformation within the mixture from that caused by the stripping of asphalt binders from the aggregate. As a result, the corrected rut depth at 20,000 passes (CRD_{20k}) provides a more accurate indication of rutting resistance than the traditional rutting parameters of the total rut depth (*TRD*) or passes to 12.5 mm rut depth ($N_{12.5}$). Furthermore, CRD_{20k} has been shown to correlate better to the field rutting data on the NCAT Test Track than *TRD* (Yin et al., 2020). The stripping number (*SN*) parameter in this analysis represents the number of passes at which stripping occurs in the mixture and is determined as the inflection point of the rut depth curve. It is typically much lower than the AASHTO-defined *SIP*. Details about the calculation of CRD_{20k} and *SN* parameters can be found elsewhere (Yin et al., 2014; Yin et al., 2020). For mixture performance evaluation, a lower CRD_{20k} and a higher *SN* is desired for better rutting resistance and moisture resistance, respectively.

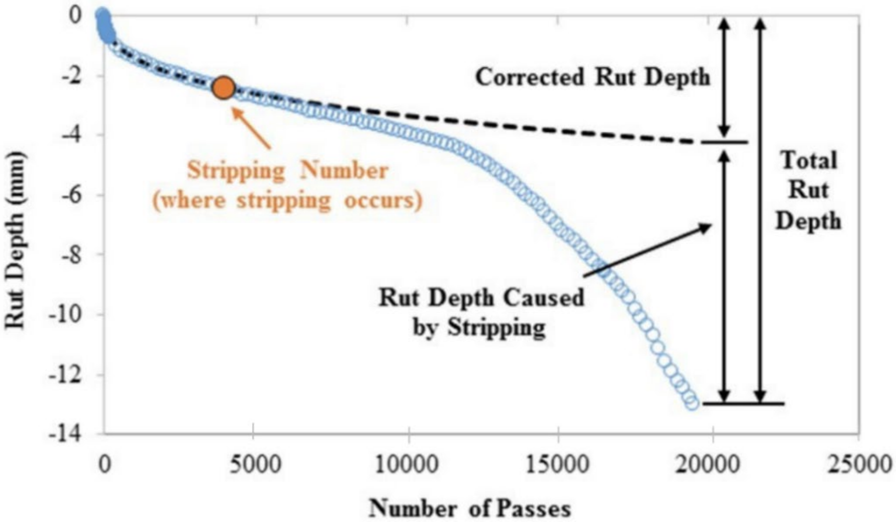
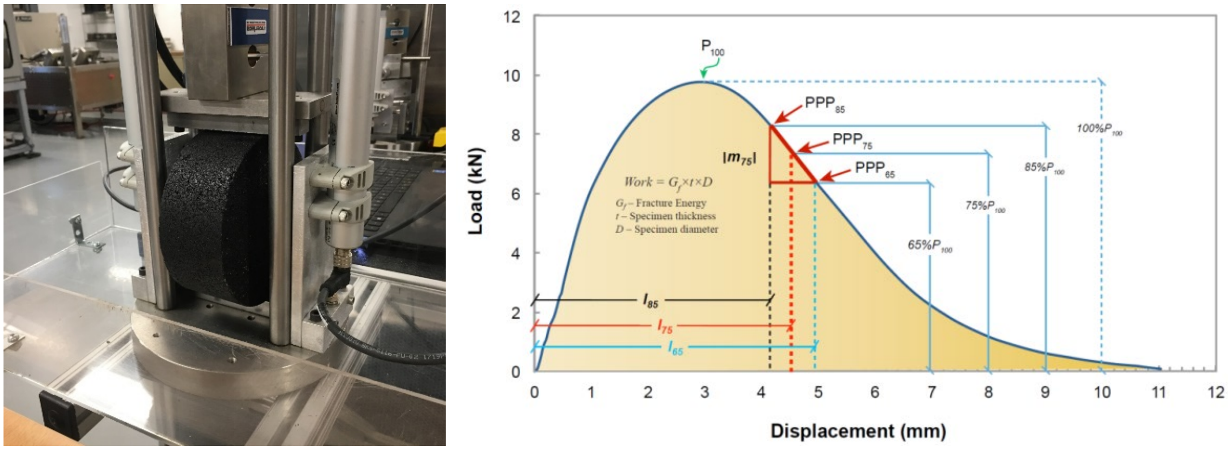


Figure 11. Alternative HWTT Data Analysis based on CRD_{20k} and *SN* Parameters

Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The IDEAL-CT was conducted to evaluate mixture resistance to intermediate-temperature cracking resistance. Testing was performed in accordance with ASTM D8225-19. The test is relatively simple as it does not require additional sample preparation beyond sample compaction.

For this test, a minimum of four 62 mm tall gyratory specimens were prepared to a target air void content of 7.0 ± 0.5%. During testing, specimens were loaded monotonically in indirect tension [Figure 12(a)] at a rate of 50 mm/min until failure while load line displacement (LLD) was recorded. Testing was performed using a device capable of sampling load and displacement data at a rapid rate (40 Hz). An example of the load versus LLD data is shown in Figure 12(b).



(a) (b)

Figure 12. Indirect Tensile Asphalt Cracking Test (a) Specimen Setup, (b) Example Load versus LLD Data (Zhou et al., 2017)

The IDEAL-CT test parameter, cracking tolerance index (CT_{Index}), is calculated using Equation 1. There are three major parameters factored into the calculation of CT_{Index}: fracture energy (G_f) defined as the area under the load-displacement curve, post-peak slope at 75% of the peak load after the peak ($|m_{75}|$), and displacement of the specimen at 75% of the peak load after the peak (l_{75}). A higher G_f and l_{75} would increase the CT_{Index} while a higher $|m_{75}|$ would lower the CT_{Index}. A higher CT_{Index} is desired for asphalt mixtures to resist intermediate-temperature cracking.

$$CT_{Index} = \frac{t}{62} * \frac{l_{75}}{D} * \frac{G_f}{|m_{75}|} * 10^6 \qquad \text{Equation 1}$$

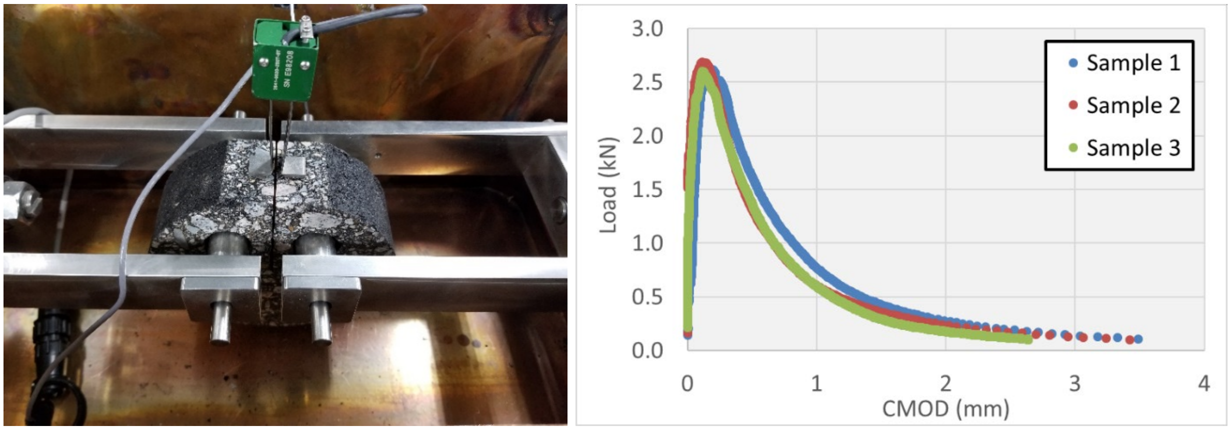
Where:

CT_{Index} = cracking tolerance index;
G_f = fracture energy (J/m^2);
$|m_{75}|$ = absolute value of the post-peak slope m_{75} (N/m);
l_{75} = displacement at 75% of the peak load after the peak (mm);
D = specimen diameter (mm); and
t = specimen thickness (mm).

Disc-shaped Compact Tension (DCT) Test

The DCT test was conducted to assess the low-temperature cracking resistance of asphalt mixtures in accordance with ASTM D 7313-13. A minimum of four replicate specimens prepared to 7.0 ± 1.0% air voids were tested. The final DCT specimens are 50 ± 5 mm thick that have been cut from a larger gyratory sample initially compacted to 160 mm tall and 150 mm in diameter. The individual test specimens are then trimmed to meet the required dimensions in ASTM D 7313-20. The critical components include a flat edge on one side of the specimen for instrumentation gage points, a 62.5 ± 5.0 mm notch down the center of the specimen from the flat edge, and two 1-inch diameter holes on each side of the notch.

The recommended test temperature from ASTM D 7313-20 is the low PG grade of the binder plus 10°C. However, because virtually all of the mixes in the benchmarking experiment used a virgin binder with a low PG grade of -28°C, the DCT test was conducted at -18°C (i.e., -28°C plus 10°C) regardless of the virgin binder grade. A single test temperature was desired to effectively compare the low-temperature cracking resistance of asphalt mixtures for the benchmarking evaluation. During testing, DCT specimens were loaded in tension by metal rods that were inserted through the specimen core holes [Figure 13(a)]. A clip gage was installed over the crack mouth prior to the start of the test to control and record the crack mouth opening displacement (CMOD). After the specimens were conditioned to the target test temperature, they were loaded into the DCT loading frame and the clip gage was installed. Initially, a seating load of 0.2 kN was applied to the specimen in tension. After the seating load was applied, the test was then performed in CMOD control with the clip gage opening at a constant rate of 0.017 mm/sec. The test was performed until the load dropped below 0.1 kN. An example of the load versus CMOD data is shown in Figure 13(b).



(a) (b)

Figure 13. Disc-shaped Compact Tension Test (a) Specimen Setup, (b) Example Load versus CMOD Data

For data analysis, the material G_f is calculated using Equation 2. The area under the load versus CMOD curve is determined through numerical integration using the trapezoid rule. A higher G_f value is desired for asphalt mixtures with better resistance to low-temperature cracking.

$$G_f = \frac{AREA}{B * (W - a)} \qquad \text{Equation 2}$$

Where:

G_f = Fracture Energy (J/m^2);

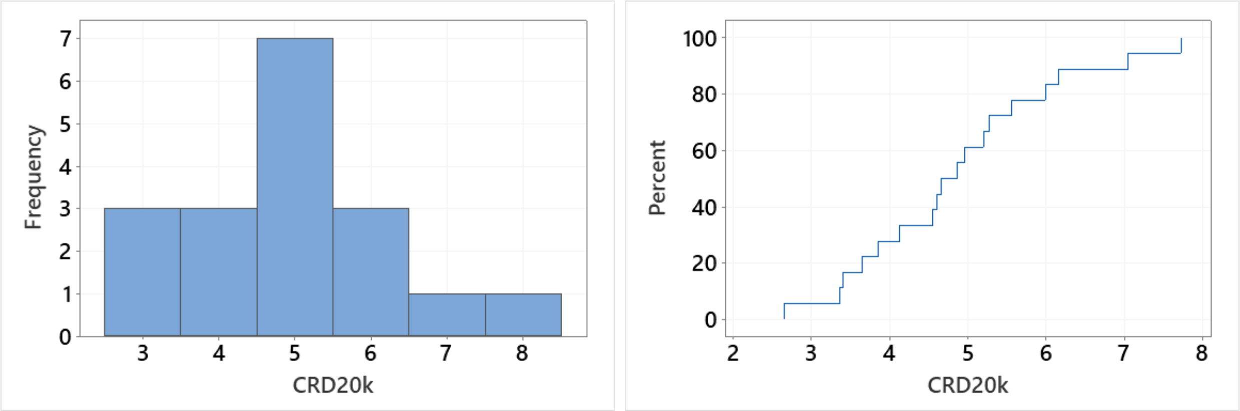
$AREA$ = Area under Load-CMOD curve;
B = Specimen Thickness (m); and
$W\text{-}a$ = Initial Ligament Length (m).

2.2 Benchmarking Test Results and Data Analysis

2.2.1 HWTT Results

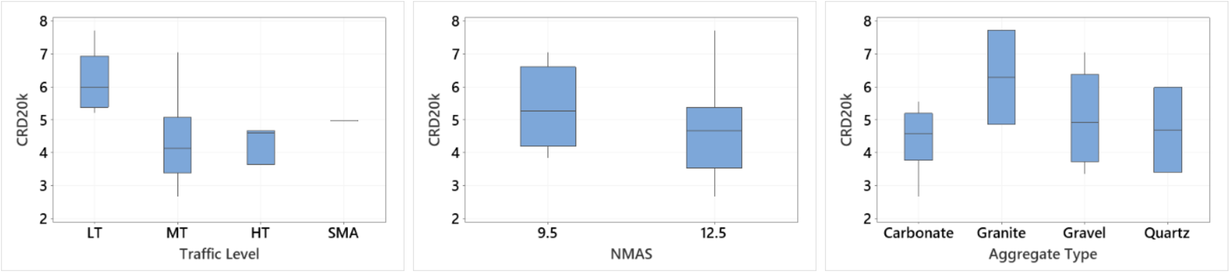
Figure 14 presents the histogram and cumulative distribution curve of CRD_{20k} at 20,000 passes for the 18 mixes in the benchmarking experiment. The CRD_{20k} values varied from 2.7 to 7.7 mm with an average of 4.9 mm. The 25th and 75th percentiles corresponded to 3.8 mm and 5.7 mm, respectively. Figure 15 presents the individual boxplot of the CRD_{20k} results grouped by traffic level, aggregate NMAS, and aggregate type, respectively. It should be noted that the boxplot results presented in this section should be interpreted with caution because the analysis is not intended to consider the interaction between different mix design variables, which may have a significant impact on the mixture performance test results. Furthermore, the analysis results are highly dependent on the size of the benchmarking database. In this case, a database of 18 mix designs is not sufficient to assess the interactions of many different mix design variables involved.

As shown Figure 15(a), the MT, HT, and SMA mixes had generally lower CRD_{20k} values and thus, were expected to have better rutting resistance than the LT mixes. However, the difference between the LT and MT mixes may not be significant if considering the wide spread of the CRD_{20k} results as indicated by the interquartile range of the boxplots. The test results in Figure 15(b) and Figure 15(c) indicated that aggregate NMAS and aggregate type did not seem to have a significant impact on the HWTT CRD_{20k} results.



(a) (b)

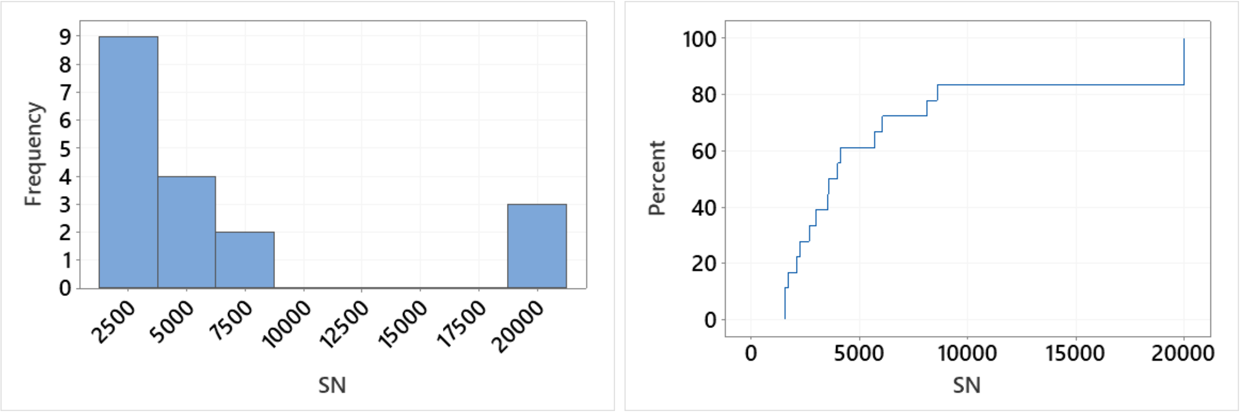
Figure 14. HWTT CRD_{20k} Results at 46°C (a) Histogram, (b) Cumulative Distribution Curve



(a) (b) (c)

Figure 15. Boxplots of HWTT CRD_{20k} Results at 46°C by (a) Traffic Level, (b) Aggregate NMAS, and (c) Aggregate Type

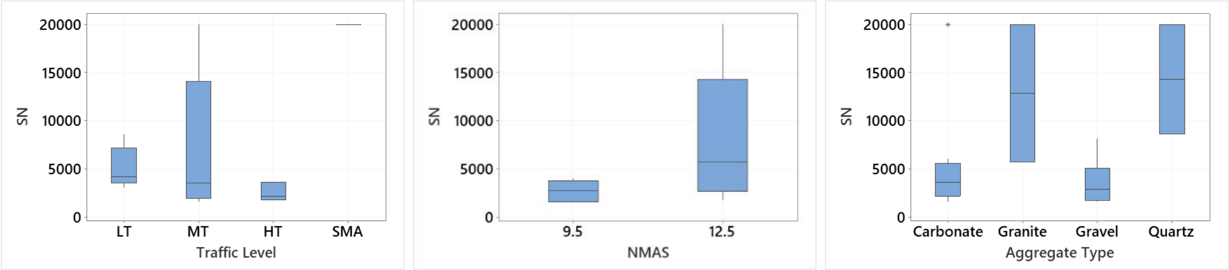
Figure 16 presents the histogram and cumulative distribution curve of HWTT *SN* results for the 18 benchmarking mixes. There were three mixes that did not exhibit a stripping phase in HWTT and thus, they are shown with a *SN* of 20,000 passes in the figures. Among the 15 mixes that showed stripping failure in HWTT, nine had a *SN* between 1,250 and 3750 passes, four between 3,750 and 6,250 passes, and two between 6,250 and 8,750 passes. The minimum *SN* result was 1,561 passes, which corresponded to a 9.5 mm MT mix with PG 58S-28 unmodified binder and 30% RAP. The 25th and 75th percentiles of the *SN* results were 2,223 and 8,248 passes, respectively.



(a) (b)

Figure 16. HWTT *SN* Results at 46°C (a) Histogram, (b) Cumulative Distribution Curve

Figure 17 presents the individual boxplot of the *SN* results grouped by traffic level, aggregate NMAS, and aggregate type, respectively. As shown in Figure 17(a), the SMA mix did not show stripping failure in HWTT and thus, is assigned with a *SN* of 20,000 passes. In most cases, the LT mixes had higher *SN* than the HT mixes, which indicated possibly improved resistance to moisture damage. The MT mixes, on the other hand, had a significantly wider range of *SN* results than the LT and HT mixes. The results in Figure 17(b) indicated that aggregate NMAS may not have a statistically significant impact on the *SN* results, although most of the 12.5 mm mixes outperformed the 9.5 mm mixes in HWTT. Finally, aggregate type seemed to have an impact on the HWTT *SN* results to a great extent. As shown in Figure 17(c), granite and quartz mixes had higher *SN* and thus, were expected to be more resistant to moisture damage than carbonate and gravel mixes.



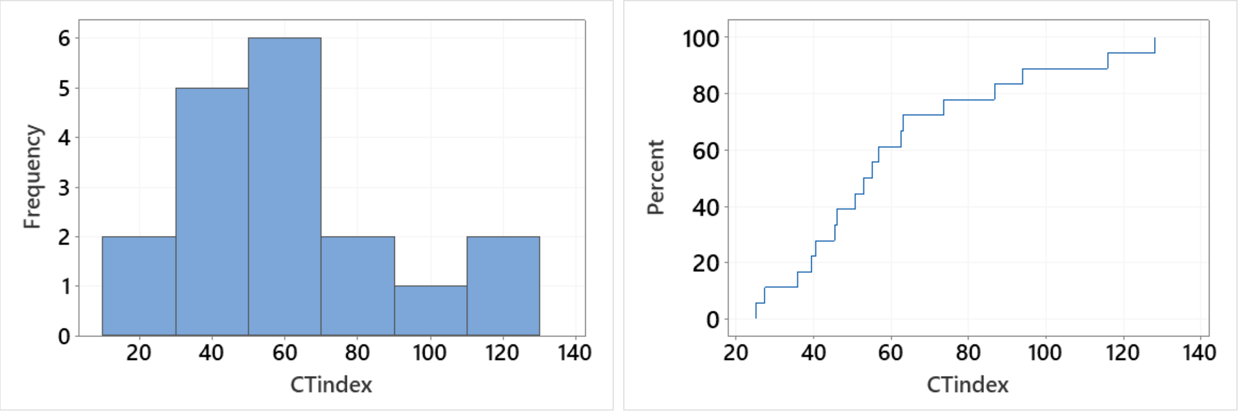
(a) (b) (c)

Figure 17. Boxplots of HWTT *SN* Results at 46°C by (a) Traffic Level, (b) Aggregate NMAS, and (c) Aggregate Type

In addition to the CRD_{20k} and *SN* results presented in Figure 14 through Figure 17, data analysis of the traditional HWTT parameters of $N_{12.5}$ and *SIP* was also conducted, and the results are presented in Appendix C.

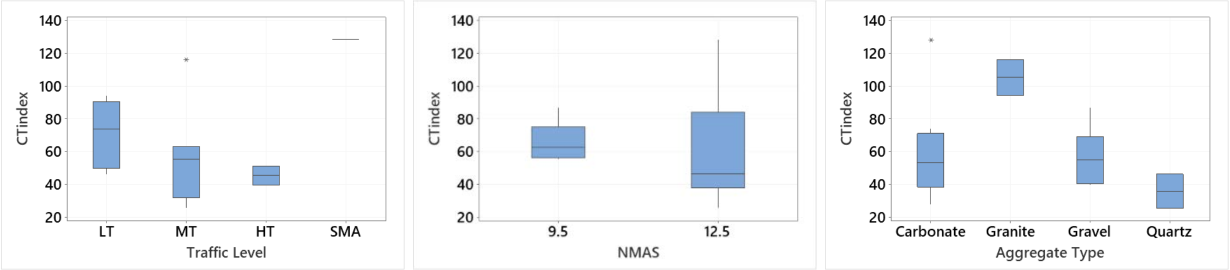
2.2.2 IDEAL-CT Results

Figure 18 presents the histogram and cumulative distribution curve of IDEAL-CT CT_{Index} results from the benchmarking experiment. Note that these results are for mixes that had been short-term aged for four hours at 135°C and then long-term aged for six hours at 135°C prior to compaction. The CT_{Index} results of the mixes ranged from 25.4 to 128.1, with an average of 61.2. The highest value is for the SMA mix. The 25th and 75th percentiles of the CT_{Index} results were 40.4 and 77.0, respectively. Figure 19 presents the individual boxplots of the CT_{Index} results grouped by traffic level, aggregate NMAS, and aggregate type, respectively. As shown in Figure 19(a), among all the Superpave dense-graded mixes, the LT mixes had the highest median CT_{Index} and thus, were expected to have the best resistance to intermediate-temperature cracking, followed by the MT mixes, and then the HT mixes. This difference was likely attributed to the difference in the asphalt binder content of the mixes because of different N_{design}. The LT mixes were designed with an N_{design} of 40 gyrations and had an average asphalt binder content of 6.0%, which was 0.1% higher than that of the MT mixes and 0.4% higher than that of the HT mixes. These results suggest that CT_{Index} is substantially affected by the asphalt binder contents of the mixes. No significant difference in the CT_{Index} results between the 9.5 mm and 12.5 mm mixes was observed in Figure 19(b). Finally, the CT_{Index} results were also affected by different aggregate types, as shown in Figure 19(c). The two granite mixes had the highest CT_{Index} results, followed by carbonate and gravel mixes, and then quartz mixes. These results indicate a possibly significant impact of aggregate type on the CT_{Index} results.



(a) (b)

Figure 18. IDEAL-CT CT_{Index} Results at 25°C (a) Histogram, (b) Cumulative Distribution Curve

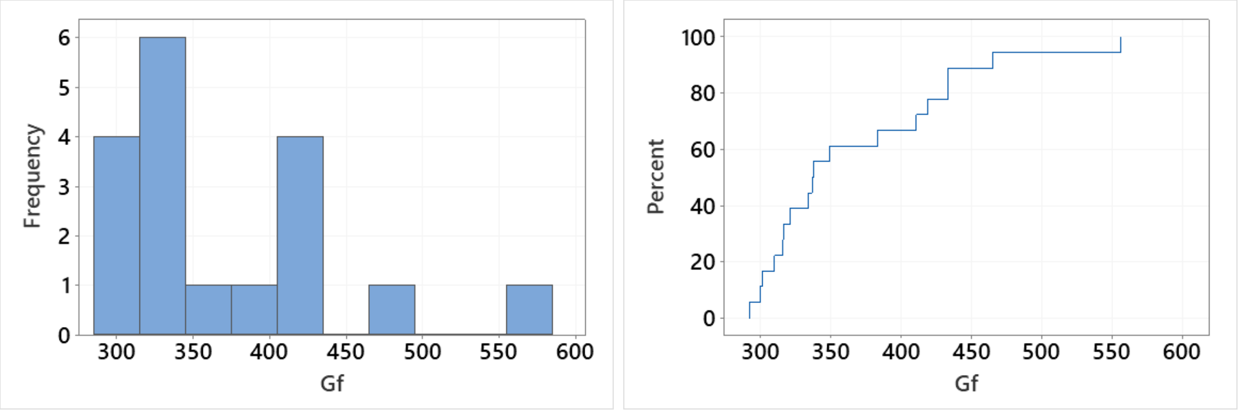


(a) (b) (c)

Figure 19. Boxplots of IDEAL-CT CT_{Index} Results at 25°C by (a) Traffic Level, (b) Aggregate NMAS, and (c) Aggregate Type

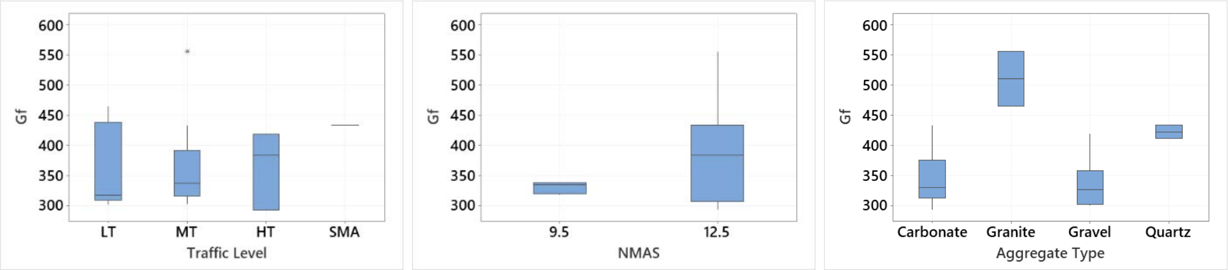
2.2.3 DCT Results

Figure 20 presents the histogram and cumulative distribution curve of the DCT G_f results for the 18 mixes in the benchmarking experiment. Note that these results are for mixes that had been short-term aged for four hours at 135°C and then long-term aged for six hours at 135°C prior to compaction. Among all the mixes, the G_f results ranged from 292.4 to 555.8 J/m^2, with an average of 367.6 J/m^2. The 25th and 75th percentiles correspond to 313.6 and 422.3 J/m^2, respectively. Figure 21 presents the individual boxplots of the DCT G_f results grouped by traffic level, aggregate NMAS, and aggregate type, respectively. As shown in Figure 21(a), there was no apparent distinction among the LT, MT, and HT mixes, which indicates that traffic level, and therefore N_{design} and asphalt content, may not be a significant factor affecting the G_f results. The results in Figure 21(b) show that overall, the 9.5 mm mixes had lower G_f results and thus, were expected to be more susceptible to low-temperature cracking than the 12.5 mm mixes. However, this difference may not be significant considering the wide spread of the G_f results of the 12.5 mm mixes as indicated by the interquartile range of the boxplot in Figure 21(b). Finally, notable differences were observed in the G_f results of the mixes with different aggregate types. As shown in Figure 21(c), granite mixes had the highest G_f results, followed by quartz mixes, and then carbonate and gravel mixes.



(a) (b)

Figure 20. DCT G_f Results at -18°C; (a) Histogram, (b) Cumulative Distribution Curve



(a) (b) (c)

Figure 21. Boxplots of DCT G_f Results at -18°C by (a) Traffic Level, (b) Aggregate NMAS, and (c) Aggregate Type

2.3 Development of Preliminary Performance Test Criteria

Based on test results of the benchmarking experiment, preliminary performance test criteria were suggested for the implementation of BMD in Wisconsin. As shown in Table 4, the performance criteria are based on the design traffic level of the mix, with four groupings of SMA, HT, MT, and LT mixes.

Table 4. Suggested Preliminary Performance Test Criteria

Traffic Level	HWTT*		IDEAL-CT$^{\#}$	DCT$^{\#}$
	CRD_{20k} (mm)	SN (passes)	CT_{Index}	G_f (J/m^2)
SMA Mix	≤ 6.0	≥ 2,000	≥ 80	≥ 400
HT Mix			≥ 40	≥ 300
MT Mix	≤ 7.0			
LT Mix	≤ 8.0			

* *test conducted on short-term aged specimens.*
$^{\#}$ *test conducted on long-term aged specimens.*

The HWTT criteria are based on the CRD_{20k} and SN parameters for the evaluation of rutting resistance and moisture susceptibility, respectively. Because rutting has not been a problem for Wisconsin mixes since the implementation of Superpave, the CRD_{20k} criteria were selected such that nearly all the mixes in the benchmarking experiment pass the respective criteria for the four mixture categories. Logically, lower CRD_{20k} criteria were suggested for mixes with higher traffic levels to ensure better rutting resistance. With the suggested maximum CRD_{20k} criteria of 6.0 mm for SMA and HT mixes, 7.0 mm for MT mixes, and 8.0 mm for LT mixes, only one MT mix in the benchmarking experiment would fail the rutting requirement, and thus, need mix design adjustments for performance improvement. For the HWTT SN parameter, a minimum criterion of 2,000 passes was suggested for all the mixes regardless of the design traffic level. This suggestion was primarily based on the findings of Yin et al. (2020), which indicated that a SN threshold of 2,000 passes successfully discriminated over 70 plant-produced asphalt mixes with and without moisture damage in the field. With the suggested SN criterion of 2,000 passes, three mixes (one HT mix and two MT mixes) in the benchmarking experiment would fail the moisture susceptibility requirement.

The preliminary IDEAL-CT CT_{Index} criteria include two levels, one for SMA mixes and the other for Superpave mixes. Although it seems logical to require higher CT_{Index} thresholds for mixes with higher traffic levels to ensure better resistance to load-related cracking, the benchmarking CT_{Index} results did not support this idea. Because Wisconsin mixes with different traffic levels are designed with different N_{design}, which result in different asphalt binder contents, and that CT_{Index} is highly dependent on the asphalt binder content of the mix, the LT mixes in the benchmarking experiment had higher CT_{Index} results than the MT and HT mixes. Therefore, instead of requiring different CT_{Index} criteria for mixes with different traffic levels, a minimum CT_{Index} of 40 was suggested as the preliminary criterion for all the Superpave mixes regardless of design traffic level. A higher CT_{Index} criterion of 80 was suggested for SMA mixes to ensure their superior cracking resistance as a premium asphalt mix for Wisconsin DOT. With these suggested CT_{Index} criteria, three MT mixes in the benchmarking experiment would fail the intermediate-temperature cracking requirement and thus, need mix design adjustments for performance improvement.

The DCT test was recommended to be conducted at 10°C above the climate-based low-temperature grade of the binder instead of that of the virgin binder in the mix. This recommendation avoids the arbitrary adjustment of DCT test temperature for mixes intentionally designed with a softer virgin binder to offset the stiffening effect of RAP and/or RAS materials. Because low-temperature cracking is not a load-related cracking distress, it is not necessary to adjust the DCT test requirements for mixes with different traffic levels. Therefore, the DCT G_f criteria were suggested to include two levels with a minimum threshold of 400 J/m^2 for SMA mixes and a minimum threshold of 300 J/m^2 for all Superpave mixes. With these suggested criteria, only one HT mix in the benchmarking experiment would fail the low-temperature cracking requirement and thus, need mix design adjustments for performance improvement.

3. BALANCED MIX DEISGN OPTIMIZATION

The research team selected five mix designs that failed the proposed BMD criteria proposed in Table 4 (benchmarking experiment) for BMD optimization. A summary of the key properties of these mix designs is shown in Table 5. The mixes selected for BMD optimization in Task 4 contained multiple levels of the following factors: NMAS (4 x 12.5 mm and 1 x 9.5 mm), Traffic Level (4 x 75 gyration designs and 1 x 100 gyration design), base binder grade (4 x PG 58S-28 and 1 x PG 52S-34), primary aggregate type (3 x carbonate, 1 x quartz, and 1 x gravel), RAP (ranging from 10 to 35%), and RAS (two mixes contained about 3% RAS while three mixes did not contain RAS).

Table 5. Summary of Mix Designs for BMD Optimization

Mix ID	NMAS (mm)	Traffic Level	N_{des}	Base Binder	Primary Aggregate Type	RAP (%)	RAS (%)
M	12.5	Medium	75	PG 58S-28	Quartz	18	3
L	12.5	Medium	75	PG 58S-28	Carbonate	10.1	3.4
K	12.5	Medium	75	PG 58S-28	Carbonate	26	0
C	12.5	High	100	PG 58S-28	Carbonate	16	0
F	9.5	Medium	75	PG 52S-34	Gravel	35	0

The research team endeavored to use a variety of strategies to optimize the BMD performance of the selected mix designs. Three of the mixes (M, L, and K) fell below the proposed CT_{Index} threshold, indicating a need to improve intermediate temperature cracking resistance. One mix fell below the proposed DCT Fracture Energy threshold, indicating a need to improve low temperature cracking resistance. Finally, one mix failed the proposed HWTT criteria, indicating the need to improve rutting and moisture damage resistance. The following strategies were employed by the research team in the optimization process:

- Add more asphalt to improve cracking resistance.
- Remove RAS to improve cracking resistance.
- Add a recycling agent to improve cracking resistance.
- Use a lower PG grade binder to improve cracking resistance.
- Use a higher MSCR grade binder to improve rutting resistance.
- Add a liquid anti-strip to reduce moisture susceptibility.

For this optimization evaluation, raw materials were provided to NCAT by the contractors for each of the five selected mix designs. All specimens for this evaluation were lab-mixed, lab-compacted specimens that were prepared and tested at NCAT. The first step was to perform a mix design verification on each of the selected mix designs. For each design, a set of N_{design} and G_{mm} specimens were prepared at the design asphalt content corresponding to 4.0% air voids. The G_{mb} and G_{mm} from these tests were then compared to the mix design. If the verification values fell within the AASHTO d2s ranges for both G_{mb} and G_{mm}, the mix design was cleared to continue to performance testing. For two of the designs (L and F), the original verification fell just outside the AASHTO d2s threshold for G_{mb}. For these designs, the contractor suggested a slight modification to the mix cold feeds that brought the G_{mb} within the acceptable range. A summary of the design verification results is shown in Table 6. Given the allowable range of the d2s thresholds for G_{mb} and G_{mm}, the calculated air voids for each of the final designs would not be exactly 4.0%. The calculated air voids using the verification data were within 0.7% of 4.0% air voids for each of the five designs.

Table 6. Summary of Mix Design Verification

Mix ID	G_{mb} (AASHTO d2s = 0.017)			G_{mm} (AASHTO d2s = 0.024)			NCAT V_a (%)
	JMF	NCAT	Difference	JMF	NCAT	Difference	
M	2.374	2.365	-0.009	2.474	2.481	0.007	4.7
L	2.419	2.425	0.006	2.519	2.528	0.009	4.1
K	2.369	2.382	0.013	2.468	2.470	0.002	3.6
C	2.428	2.442	0.014	2.529	2.551	0.022	4.3
F	2.377	2.378	0.001	2.476	2.461	-0.015	3.4

The same mixture performance tests and laboratory aging protocols were used in this evaluation as were used in the benchmarking experiment. Short-term aging (four hours at 135°C) plus long-term laboratory aging (six hours at 135°C on loose mix) were used for the IDEAL-CT (ASTM D8225-19) and DCT (ASTM D7313-13), while short-term aging only was performed on the Hamburg Wheel-Track Test (HWTT) (AASHTO T324-19) specimens. All performance tests were prepared at the asphalt content corresponding to the regressed air voids level of 3.0% V_a from the provided mix design.

The first step in optimizing each mix was to attempt a mix modification to improve the test result that failed the benchmarking criteria. The test result that failed the criteria proposed in Table 4 was referred to by the research team as the ‘critical’ test for that mix design. A variety of optimization strategies were used to attempt to improve the critical test results. After the critical test was optimized to pass the recommended criteria from the benchmarking experiment, the test results from the remaining two performance tests were verified. For example, for Mix M, IDEAL-CT was the critical test since the CT_{Index} from the benchmarking experiment fell below the proposed BMD criteria. After CT_{Index} was optimized for Mix M, DCT and HWTT were then verified for the optimized mix. Finally, volumetric properties (i.e., G_{mb} and G_{mm}) were verified for the final optimized mix. A flowchart summary of the work performed in the optimization study is shown in Figure 22.

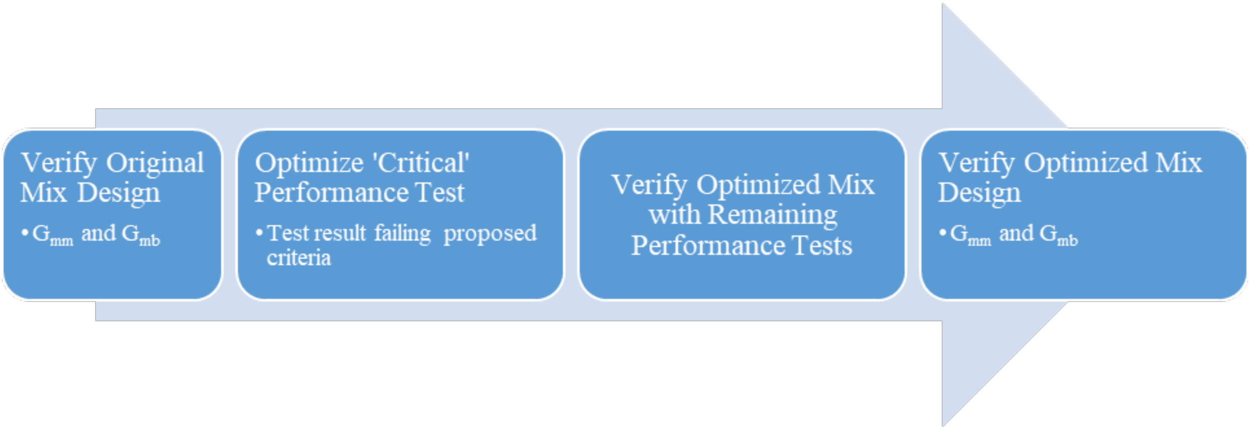


Figure 22. Work Flow Summary for BMD Optimization Experiment

Mix M

Mix M failed the proposed criteria for IDEAL-CT with an average CT_{Index} of 25.4. Hence, IDEAL-CT was the critical test for Mix M. The research team wanted to explore two options for improving this mix – redesigning the mix without RAS (the original mix contained 3% RAS) and increasing the asphalt content to meet the minimum CT_{Index} criteria of 40. The contractor noted that their RAS was actually a 50/50 blend of processed shingles and manufactured sand. For the RAP only mix, 1.5% each was added to the manufactured sand and RAP stockpiles to offset the lack of RAS in the design.

For the IDEAL-CT optimization, testing was performed at 5.3% and 5.8% total asphalt content for both blends with and without RAS. These asphalt contents correspond to the regressed air voids optimum and the regressed air voids optimum + 0.5% asphalt content. A summary of the IDEAL-CT results is shown in Figure 23. A more detailed statistical summary of all the test results from the BMD optimization experiment is provided in Appendix D. The data point on Figure 23 labeled 'Contractor' are the test results from the benchmarking experiment for this mix. These are the test results collected on specimens fabricated by the contractor and tested at NCAT. This nomenclature will be used throughout the remainder of this report. These results are included to provide a frame of reference for the between lab variability seen in the mixture performance tests when specimens are fabricated in two different labs and tested by the same lab.

First, Figure 23 shows reasonable agreement between the CT_{Index} results from the specimens fabricated by the contractor (avg. $CT_{Index} = 25.4$) and the specimens fabricated and tested at NCAT (avg. $CT_{Index} = 30.6$) for the 3% RAS blend at 5.3% total asphalt content. From the regression of CT_{Index} versus asphalt content in Figure 23, the asphalt content for each blend that satisfied a minimum CT_{Index} of 40 could be determined. For the blend with 3% RAS, 5.9% total asphalt was estimated to meet the minimum CT_{Index} of 40. For the blend without RAS, only 5.5% total asphalt was required. Hence, there was a 0.4% increase in the binder required to meeting the minimum CT_{Index} criteria for this particular mix when 3% RAS was included. These CT_{Index} optimized blends were then verified in the HWTT and DCT.

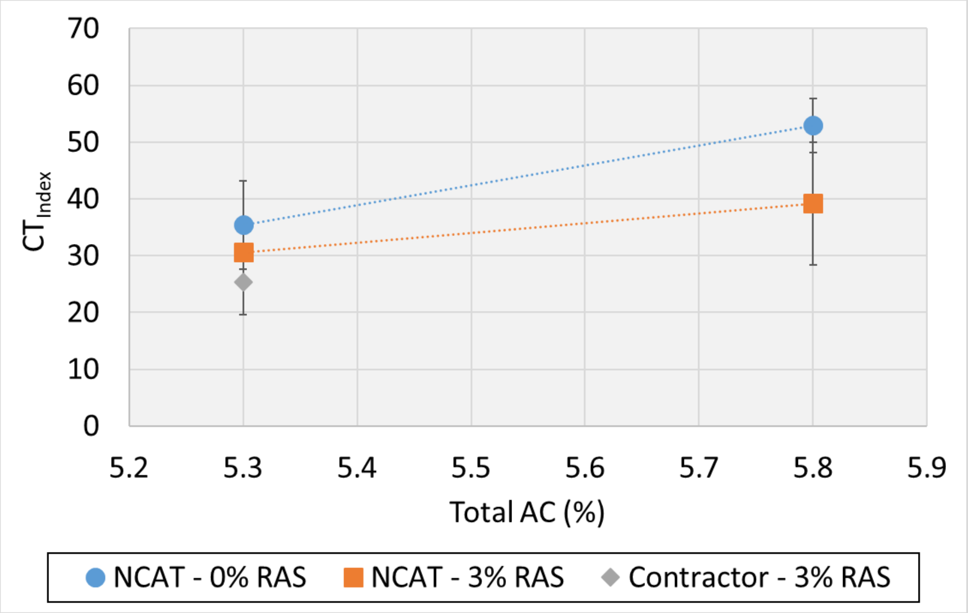


Figure 23. Mix M IDEAL-CT Optimization

Table 7 summarizes the average results of the HWTT and DCT testing for Mix M. The results shown are for the benchmarking (contractor) samples and for the blends with and without RAS at 5.9% and 5.5% AC, respectively. Table 7 shows that both optimized blends (with and without RAS) easily passed the proposed HWTT and DCT criteria. Hence, either of these blends would be considered acceptable balanced mix designs.

Table 7. Mix M Optimization Summary – Average Results

AC %	RAS %	Specimen Fabrication	DCT G_f (J/m^2)	HWTT CRD_{20k} (mm)	HWTT SN (passes)
			Min. 300	Max 7.0	Min. 2,000
5.3	3	Contractor	433	3.4	>20,000
5.9	3	NCAT	476	4.3	>20,000
5.5	0	NCAT	424	3.8	7,920

Finally, the volumetrics for the final optimized blends along with the original design verification data for Mix M are provided in Table 8. Recall that the design verification was performed at the asphalt content corresponding to 4.0% air voids and not at the regressed air voids asphalt content. The optimized 3% RAS blend included 0.7% more asphalt than the original design, which corresponds to a 1.8% reduction in air voids at N_{des} (4.7% vs. 2.9% V_a). The optimized 0% RAS blend included 0.3% more asphalt than the original design, which corresponds to a 0.7% reduction in V_a. The volumetrics of the optimized 0% RAS blend were in better agreement with the original design than the volumetrics of the optimized 3% RAS blend.

Table 8. Mix M – Volumetrics Summary

Blend ID	AC (%)	NCAT G_{mb}	NCAT G_{mm}	V_a (%)
Design Verify (4.0% V_a Target)	5.2	2.365	2.481	4.7
3% RAS	5.9	2.383	2.455	2.9
0% RAS	5.5	2.372	2.470	4.0

Mix L

Mix L failed the proposed criteria for IDEAL-CT with an average CT_{Index} of 36.0. Therefore, IDEAL-CT was the critical test for Mix L. The research team decided to use a rejuvenator to improve the cracking resistance of this mix. The contractor that supplied the mix suggested a rejuvenator given some past laboratory experience with the product.

Figure 24 summarizes the IDEAL-CT optimization for Mix L. IDEAL-CT testing was performed both without rejuvenator and with 3% rejuvenator by weight of total binder. This rejuvenator dosage rate was selected based on past experience with rejuvenator dosages and was not the result of a binder-based rejuvenator optimization study. Instead, the research team attempted to select a rejuvenator dosage that would allow this mix to meet the desired minimum CT_{Index} threshold of 40. Figure 24 shows that the benchmarking CT_{Index} results (avg. CT_{Index} = 36.0) and optimization CT_{Index} results (avg. CT_{Index} = 34.4) agree extremely well for mix L with no rejuvenator. Although the results indicated that 1% rejuvenator dosage (by weight of total binder) would hit the minimum CT_{Index} threshold, the research team elected to use 1.5% rejuvenator (by weight of total binder) as the optimized dosage to provide a cushion for the design above the CT_{Index} threshold.

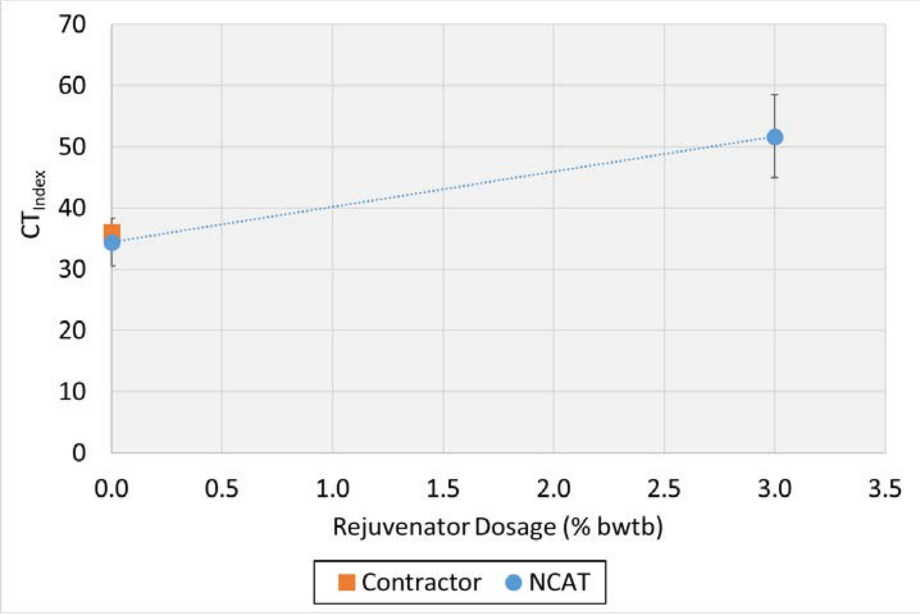


Figure 24. Mix L IDEAL-CT Optimization

HWTT and DCT were verified for Mix L with 1.5% rejuvenator (Table 9). Both HWTT and DCT passed the proposed BMD criteria with no concerns. Table 10 shows the final volumetric check for Mix L at 5.8% asphalt content with 1.5% rejuvenator. Bear in mind that 5.8% was the total asphalt content from the JMF corresponding to the regressed air voids level of 3.0%. Relative to the original design verification at 5.5% asphalt content at 4.0% design air voids, the optimized mix contained 0.3% more asphalt and air voids were reduced by 0.6%.

Table 9. Mix L Optimization Summary – Average Results

AC %	Rejuvenator Dosage (%bwtb)	Specimen Fabrication	DCT G_f (J/m^2)	HWTT CRD_{20k} (mm)	HWTT SN (passes)
			Min. 300	Max 7.0	Min. 2,000
5.8	0	Contractor	349	2.7	6,076
5.8	1.5	NCAT	379	3.6	7,377

Table 10. Mix L – Volumetrics Summary

Blend ID	AC (%)	NCAT G_{mb}	NCAT G_{mm}	V_a (%)
Design Verify – no Rejuvenator (4.0% V_a Target)	5.5	2.425	2.528	4.1
1.5% Rejuvenator	5.8	2.428	2.516	3.5

Mix K

Mix K failed the proposed criteria for IDEAL-CT with an average CT_{Index} of 27.5. Hence, IDEAL-CT was the critical test for Mix K. The original base binder grade for this mix was a PG 58S-28 binder. The research team elected to attempt two approaches for optimizing CT_{Index} for this mix: a) using a binder with a lower low PG grade (PG 52S-34, PG 58S-28, or PG 58H-34), and b) increasing the total asphalt content of the mix.

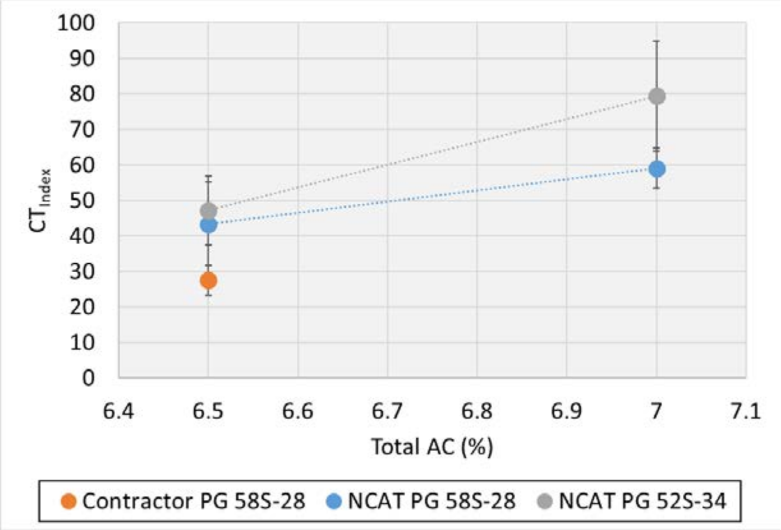


Figure 25. Mix K IDEAL-CT Optimization

For the Mix K IDEAL-CT optimization, testing was performed at both 6.5% and 7.0% asphalt content with two different binder grades: the original PG 58S-28 and a softer PG 52S-34.

Comparing the benchmarking (contractor) results to the NCAT results at 6.5% asphalt content with the PG 58S-28 binder shows an apparent inconsistency. The samples provided to NCAT by the contractor during the benchmarking experiment had an average CT_{Index} of 27.5 while the samples made at NCAT with the same asphalt content and binder yielded an average CT_{Index} of 43.4, which was above the proposed CT_{Index} threshold of 40. This difference is likely due to lab-to-lab variability in fabricating specimens. However, the research team decided to proceed with a modification to improve the cracking resistance of this mix rather than leave it "as-is". For these base binders, the research team elected to select an asphalt content for each binder where the mix would achieve a CT_{Index} threshold of 50. For the PG 58S-28 binder, this "performance optimized" asphalt content was 6.8%, while for the PG 52S-34 binder, the "performance optimized" asphalt content was 6.6%.

The next step was to validate HWTT and DCT for the optimized designs. A summary of these results is shown in Table 11. Achieving a passing HWTT result proved problematic for this particular mix. The PG 52S-34 binder, while suitable for CT_{Index}, was not viable for rutting for this particular mix as the HWTT test results fell substantially short of the proposed criteria. Next, the mix with PG 58-28S binder was verified with the CT_{Index} optimized asphalt content of 6.8%. However, this variation barely failed the corrected rut depth maximum rut depth criteria of 7.0 mm at 20,000 passes.

Table 11. Mix K Optimization Summary – Average Results

AC %	Binder Grade	Specimen Fabrication	DCT G_f (J/m^2)	HWTT CRD_{20k} (mm)	HWTT SN (passes)	CT_{Index}
			Min. 300	Max 7.0	Min. 2,000	Min. 40
6.5	PG 58S-28	Contractor	310	4.1	2,253	27.5
6.8	PG 58S-28	NCAT	n/a	7.3	2,405	52.9
6.6	PG 52S-34	NCAT	n/a	10.7	1,061	53.4
6.5	PG 58H-34	NCAT	449	5.1	2,319	43.6

At this point, the research team elected to try a third binder with Mix K. A PG 58H-34 was selected since its higher MSCR grade was expected to improve rutting resistance. The mix with this PG 58H-34 binder at the original regressed air voids asphalt content of 6.5% passed the proposed HWTT criteria. After passing the HWTT criteria, DCT and IDEAL-CT for Mix K were verified with the PG 58H-34 binder. DCT easily passed the proposed minimum criteria of 300, and the CT_{Index} was also above the proposed minimum criteria of 40. Ultimately, the performance optimization of Mix K was accomplished by switching the base binder grade from a PG 58S-28 to a PG 58H-34. The final volumetric verification for Mix K is shown in Table 12. Relative to the original design verification at 6.2% asphalt content for 4.0% air voids, the optimized mix contained 0.3% more asphalt and air voids were reduced by 0.9%.

Table 12. Mix K– Volumetrics Summary

Blend ID	AC (%)	NCAT G_{mb}	NCAT G_{mm}	V_a (%)
Design Verify – PG 58S-28 (4.0% V_a Target)	6.2	2.382	2.470	3.6
Optimized Mix - PG 58H-34	6.5	2.394	2.461	2.7

Mix C

Mix C failed the proposed criteria for DCT with an average G_f of 292 J/m^2. Hence, DCT was the critical test for Mix C. The original base binder for Mix C was a PG 58S-28. The research team elected to try to improve the DCT results for this mix by using a binder with a lower low PG grade (PG 58S-34). It should be noted that this mix was the only high traffic mix design in the optimization study.

The DCT optimization results for Mix C are shown in Figure 25. DCT was performed at NCAT using both the original PG 58S-28 binder and a PG 58S-34 binder provided by the contractor. The regressed air voids asphalt content of 5.5% from the JMF was used for all tests. First of all, the results for the benchmarking specimens and the results for the specimens made at NCAT with the same binder grade compare reasonably well. The benchmarking experiment specimens yielded a DCT G_f of 292 J/m^2 while the specimens fabricated at NCAT yielded a DCT G_f of 319 J/m^2, which is just above the proposed criteria. Since the difference was only about 10% of the average, those results are considered reasonably close. Changing the base binder grade of the mix from a PG 58S-28 to a PG 58S-34 increased the DCT G_f from 319 to 356 J/m^2 – a 12% increase. While not a statistical increase (two-tailed two-sample t-test p-value = 0.104 > α = 0.05), this was a practical increase in the DCT G_f that provided a buffer above the minimum design value.

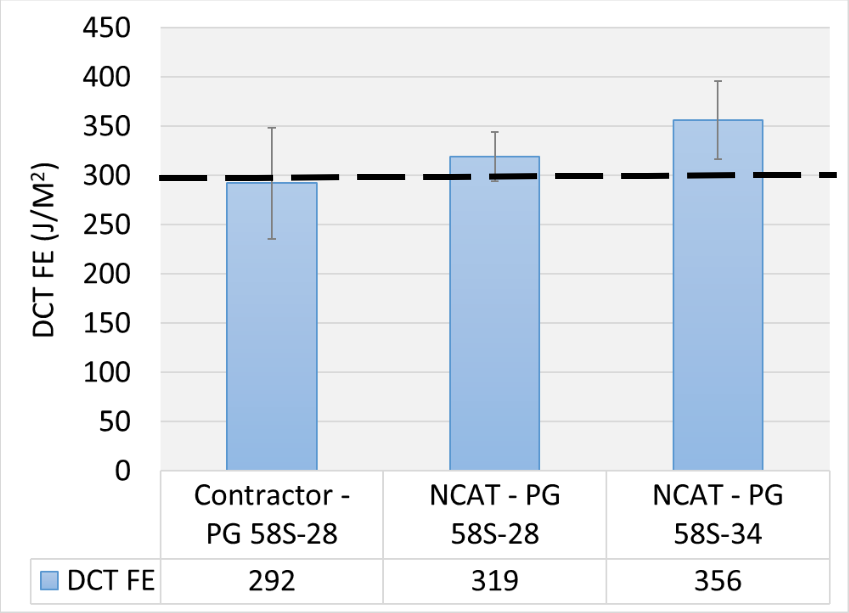


Figure 25. Mix C DCT Optimization

After using DCT to select the PG 58S-34 binder for this mix, HWTT and IDEAL-CT were verified for this design. A summary of the average HWTT and IDEAL-CT results are shown in Table 13. The HWTT results for the PG 58S-34 binder had a passing corrected rut depth (4.2 mm versus a suggested maximum of 6.0 mm for a high traffic mix), but the stripping number failed the recommended performance criteria from the benchmarking experiment (1,665 versus a suggested minimum of 2,000). The research team elected to add a LAS agent to the binder to improve the moisture resistance of the mix in the HWTT. The LAS was blended with the binder at a typical dosage rate of 0.5% of the total binder weight. The addition of LAS improved the HWTT stripping number results above the minimum design threshold of 2,000 passes.

Unfortunately, the final verification of IDEAL-CT with the PG 58S-34 base binder and 0.5% LAS agent yielded an average CT_{Index} of 32.2, below the proposed minimum of 40. Given the average CT_{Index} from the benchmarking experiment was well above the minimum value of 40, the research team had been operating under the assumption that CT_{Index} was unlikely to fail the verification testing if a softer binder than the original base binder was used (PG 58S-34 instead of a PG 58S-28). This is likely another example of between-lab variability in specimen preparation causing an unexpected difference in IDEAL-CT test results.

Table 13. Mix C Optimization Summary – Average Results

AC %	Binder Grade	Specimen Origin	Liquid Anti-Strip (%tbw)	HWTT CRD_{20k} (mm)	HWTT *SN* (passes)	CT_{Index}
				Max 6.0	Min. 2,000	Min. 40
5.5	PG 58S-28	Contractor	0	3.7	3,579	50.9
5.5	PG 58S-34	NCAT	0	4.2	1,665	n/a
5.5	PG 58S-34	NCAT	0.5	3.9	2,405	32.2

The final volumetric verification for Mix C is shown in Table 14. Relative to the original design verification at 5.2% asphalt content at 4.0% design air voids, the optimized mix contained 0.3% more asphalt and air voids were reduced by 0.6%.

Table 14. Mix C – Volumetrics Summary

Blend ID	AC (%)	NCAT G_{mb}	NCAT G_{mm}	V_a (%)
Design Verify – PG 58S-28 (4.0% V_a Target)	5.2	2.442	2.551	4.3
Optimized Mix - PG 58S-34	5.5	2.460	2.555	3.7

Mix F

Mix F failed the proposed criteria for HWTT with a corrected rut depth at 20,000 passes of 7.1 mm (versus the proposed maximum of 7.0 mm) and a stripping number of 1,573 passes (versus the proposed minimum of 2,000 passes). Hence, HWTT was the critical test for Mix F. The research team elected to first attempt improving the HWTT results of this mix by using a LAS. The contractor-recommended LAS was used for this mix at a dosage rate of 0.5% by weight of total binder. Additionally, the use of a binder with a higher MSCR grade (PG 58H-34) was explored as well.

The results of the Mix F optimization study are summarized in Table 15. First of all, the specimens prepared at NCAT with the original binder (PG 52S-34) and no LAS did not perform as well in the HWTT as the specimens from the benchmarking experiment (contractor). The two sets of data had comparable stripping numbers (1,573 vs 1,317 passes), but the NCAT prepared specimens had about a 3 mm greater corrected rut depth than the benchmarking results. Adding the LAS improved the HWTT results, but not to the degree needed to pass the proposed performance criteria. Adding LAS agent improved the CRD_{20k} by about 2 mm and the SN by about 300 passes for the mix with the PG 52S-34 binder. The next step was to use another binder with the same -34 low grade but an improved MSCR grade. Mix F was tested with the PG 58H-34 binder, with and without LAS. Without LAS, the mix did pass the proposed HWTT performance criteria – albeit very narrowly in terms of stripping number. With LAS, the SN improved by 368 passes relative to the mix with no LAS. The research team elected to select the PG 58H-34 binder with 0.5% LAS for the optimized mix to provide a buffer above the minimum threshold for the stripping number. The IDEAL-CT and DCT tests were then verified for the optimized mix, and the results of those tests were comfortably in excess of the proposed criteria.

Table 15. Mix F Optimization Summary – Average Results

AC %	Binder Grade	Specimen Fabrication	LAS (%tbw)	HWTT CRD_{20k} (mm)	HWTT *SN* (passes)	CT_{Index}	DCT G_f (J/m^2)
				Max 7.0	Min. 2,000	Min. 40	Min. 300
6.4	PG 52S-34	Contractor	0	7.1	1,573	60.6	337
6.4	PG 52S-34	NCAT	0	10.5	1,317	n/a	n/a
6.4	PG 52S-34	NCAT	0.5	8.5	1,661	n/a	n/a
6.4	PG 58H-34	NCAT	0	6.1	2,189	n/a	n/a
6.4	PG 58H-34	NCAT	0.5	6.5	2,557	63.6	416

The final volumetric verification for Mix F is shown in Table 16. Relative to the original design verification at 6.0% asphalt content at 4.0% air voids, the optimized mix contained 0.4% more asphalt and air voids were reduced by 1.3%.

Table 16. Mix F – Volumetrics Summary

Blend ID	AC (%)	NCAT G_{mb}	NCAT G_{mm}	V_a (%)
Design Verify – PG 52S-34 (4.0% V_a Target)	6.0	2.378	2.461	3.4
Optimized Mix - PG 58S-34	6.4	2.387	2.439	2.1

4. ECONOMIC ANALYSIS TO COMPARE MIX OPTIMIZATION STRATEGIES

A cost analysis was conducted to determine the potential mix cost impacts to meet the proposed BMD specifications. As explained in Chapter 3, at least one mix adjustment strategy was used to optimize five mixes. For three of the five mixes, one adjustment was found to satisfactorily meet the proposed criteria and no additional strategies were tested. Therefore, the cost analysis for these three mixes presented in this section is based on the additional cost of the optimized mixes with respect to the original mix designs.

For asphalt mix production and paving, costs can generally be assigned to one of four categories: materials, plant production, trucking, and laydown operations. (Copeland, 2011). For the analysis presented in this section, only the cost of materials was considered. The cost associated with each material was based on information gathered from different sources. Table 17 summarizes the average cost of materials used in this analysis and the source of information. The representative costs of virgin and modified asphalt binders and virgin aggregate were obtained from the latest NAPA "Asphalt Pavement Industry Survey on Recycled Materials and Warm Mix Asphalt: 2019" (Williams et. al, 2020). The average prices of RAP and RAS per ton were obtained from the Wisconsin Asphalt Pavement Association (WAPA). The cost of rejuvenator used was based on the average price reported by two rejuvenator suppliers. Lastly, the cost for adding 0.5% LAS agent by weight of the mixture was based on data reported by Christensen in 2015.

Table 17. Representative Cost of Materials

Material	Representative Cost, \$/Ton	Reference/Source
Virgin Asphalt	500	Williams et al., 2020
Modified Asphalt	646	Williams et al., 2020
Virgin Aggregate	10.8	Williams et al., 2020
RAP	9.0	WAPA, 2020
RAS	30.0	WAPA, 2020
Rejuvenator	1,650	Rejuvenator Suppliers, 2020
Liquid Anti-strip[1]	0.5	Christensen et al, 2015

[1] $/ton of asphalt mix

Mix M

Mix M had to be modified to meet the proposed CT_{Index} criterion. Two alternative modifications were evaluated. For optimization 1M, the total asphalt content of the mix was increased from 5.3% to 5.9%. For optimization 2M, the RAS was eliminated, and the total asphalt content was increased from 5.3% to 5.5%. Table 18 presents the materials costs for the original mix and the two optimized mixes. This table also indicates the percentage of each material in the mixes. As indicated in Table 18, the modifications for the optimized mixes 1M and 2M increased the materials cost of the mix by \$2.94 and \$3.26, respectively. The strategy to increase the asphalt content by 0.6% is a lower cost option compared to eliminating RAS and increasing the asphalt content by 0.2%.

Table 18. Cost Comparison of Original and BMD Optimized Mix M

Materials	Percentage of the Mix Cost		
	Original Mix	Optimized Mix 1M	Optimized Mix 2M
RAP	18.0	18.0	18.0
RAS	3.0	3.0	0.0
Virgin Asphalt	4.1	4.7	5.0
Virgin Aggregate	74.9	74.3	77.0
Mix Cost, $/ton	30.23	33.17	33.49
Cost Difference $/ton (Optimized Mix – Original Mix)		2.94	3.26
% Cost Increase		9.7%	10.8%

Mix L

Mix L also had to be modified to meet the proposed CT_{Index} criterion. The optimization strategy evaluated for this mix was to incorporate a rejuvenator at a dosage of 1.5% by weight of the total asphalt content. As indicated in Table 19, this modification would increase the materials cost of the mix by $2.30/ton.

Table 19. Cost Comparison of Original and BMD Optimized Mix L

Materials	Percentage of the Mix Cost	
	Original Mix	Optimized Mix L1
RAP	10.1	10.1
RAS	3.4	3.4
Virgin Asphalt	4.2	4.4
Virgin Aggregate	82.3	82.0
Rejuvenator	0.0	0.09
Mix Cost, $/ton	30.82	33.12
Cost Difference $/ton		2.30
% Cost Increase		7.5%

Mix K

Mix K also had to be modified to meet the proposed CT_{Index} criterion. The optimization strategy evaluated for this mix was to change the asphalt binder from a PG 58S-28 to a PG58H-34. As shown in Table 20, this modification would increase the cost of the mix from $36.78 to $44.67 per ton, a difference of $7.89/ton. This difference in cost is solely due to switching to a modified asphalt binder. As presented in Table 17, the cost difference between a modified asphalt binder and an unmodified binder is $146.25/ton.

Table 20. Cost Comparison of Original and BMD Optimized Mix K

Materials	Percentage of the Mix Cost	
	Original Mix	Optimized Mix K1
RAP	26	26
Virgin Asphalt	5.4	5.4
Virgin Aggregate	68.6	68.6
Binder Grade	PG 58S-28	PG 58H-34
Mix Cost, $/ton	36.78	44.67
Cost Difference $/ton		7.89
% Cost Increase		21.5%

Mix C

Mix C had to be modified to meet the proposed DCT criterion. The first optimization strategy was to use a softer binder (PG 58S-34). Although this strategy resulted in a passing the DCT G_f, it failed the HWTT stripping criterion. The mix was further modified by adding 0.5% of a LAS agent. This modification resulted in a failing CT_{Index}. No further modifications were evaluated. Although this mix was not optimized to pass all the performance test thresholds, costs were determined for the evaluated modifications. As presented in Table 21, the cost of the mix increased by $7.02, and $7.52 per ton with modification C1 and C2, respectively. As with Mix K, the cost differences for this mix are mainly due to the change to a modified asphalt binder.

Table 21. Cost Comparison of Original and BMD Modified Mix C

Materials	Percentage of the Mix Cost		
	Original Mix	Modification C1	Modification C2
RAP	16.0	16.0	16.0
Virgin Asphalt	4.8	4.8	4.8
Virgin Aggregate	79.2	79.2	79.2
Binder Grade	PG 58S-28	PG 58S-34	PG 58S-34
LAS	0	0	0.5
Mix Cost, $/ton	34.02	41.04	41.54
Cost Difference $/ton		7.02	7.52
% Cost Increase		20.6%	21.2%

Mix F

Mix F was modified to pass the proposed HWTT rutting and stripping criteria. Interestingly, Mix F had one of the highest RAP contents among the mixes in the study, which would normally be expected to provide good rutting resistance, but this was the only mix that used a -34 low temperature grade binder. The first strategy evaluated to improve HWTT results was to add a LAS agent, but this modification did not yield passing HWTT results. As presented in Table 22, two additional modifications were evaluated. The second modification evaluated was to change the asphalt binder from a PG 52S-34 to a PG 58H-34. This modification resulted in a satisfactory rutting parameter but a marginally passing stripping parameter. The third modification combined the first two strategies and was found to successfully meet all of the proposed BMD criteria. Table

22 shows that changing to a modified asphalt binder increased the cost of the mix by $6.87, and adding a LAS increased the cost of the mix by an additional $0.50.

Table 22. Cost Comparison of Original and BMD Optimized Mix F

Materials	Percentage of the Mix Cost		
	Original Mix	Optimized Mix F1	Optimized Mix F2
RAP	35.0	35.0	35.0
Virgin Asphalt	4.7	4.7	4.7
Virgin Aggregate	60.3	60.3	60.3
Binder Grade	PG 52S-34	PG 58H-34	PG 58H-34
LAS	0.0	0.0	0.5
Mix Cost, $/ton	33.19	40.06	40.56
Cost Difference, $/ton		6.87	7.37
% Cost Increase		20.7%	22.2%

The simple cost analysis indicates that modifications of some mixes to meet the proposed BMD criteria will likely increase the materials cost by approximately 8 to 22%. It is important to remember that only seven mixes evaluated in the benchmarking experiment failed to meet all of the proposed BMD criteria, so the majority of current Wisconsin mixes will not likely require any changes if the proposed BMD criteria are implemented. The modification strategies evaluated in this study represent the more obvious strategies as suggested by experienced mix designers in Wisconsin. However, mix designers motivated by the low-bid pavement construction industry will certainly explore many other design modification strategies to determine the most cost-effective options for their materials.

In order to improve load-related cracking resistance, as evaluated with the IDEAL-CT test, the cost analysis suggested that using a rejuvenator may be an economical approach. Adding more asphalt to a mix is a technically feasible option to increasing cracking resistance, but it may not be the most cost-effective option for certain mix designs. Reducing or eliminating recycled materials as a strategy to improve cracking resistance was not thoroughly evaluated, but the one case of eliminating RAS was found to be less economical than just increasing the asphalt content.

Only one case was evaluated to improve resistance to thermal cracking as indicated by the DCT test. The benchmarking analysis indicated that carbonate and gravel mixes tend to have lower DCT results. The mix evaluated to improve its G_f was one of the mixes containing a carbonate aggregate. However, the strategy explored for improving its low temperature cracking resistance was to use a softer low-temperature grade. Although that did improve G_f, it compromised the mixture’s rutting and stripping resistance and required a liquid anti-strip additive to overcome that issue. Further evaluations may be worthwhile to explore the cost effectiveness of reducing the carbonate aggregate content of the mix as a strategy to mitigate thermal cracking. Only one mix was evaluated to improve its rutting and moisture damage resistance as evaluated with the HWTT. The fix was to use a modified binder with better high-temperature stiffness and an antistripping agent, but this would result in more than a 20% cost increase. Other possible modifications that could be explored would include aggregate type and/or gradation changes. To evaluate the cost effectiveness of those options would require specific cost information for each aggregate and recycled component in the mixes.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objective of this project was to evaluate performance-based methodologies for asphalt mix design and develop a preliminary BMD specification for WisDOT projects. To that end, a comprehensive work plan was proposed and executed that included conducting a literature review, interviewing Wisconsin mix designers, conducting a BMD workshop, benchmarking existing WisDOT mix designs, modifying selected mix designs for improved performance, and conducting a cost analysis of mix design modifications. The main findings and conclusions of the project are summarized as follows:

5.1.1 Mix Designer Interviews

Seven experienced Wisconsin asphalt mix designers were interviewed to gather information regarding mix design practices and expectations regarding BMD. It is important to point out that these interviews were conducted in March 2020. Since BMD is a fast-moving target, some of the answers provided by the responded related to their BMD experience may be different today than reported last year.

- The majority of mix designs in Wisconsin are for medium and low traffic projects. Based on the responses gather, about half of the mix designs are in the MT category and about 40% are in the LT category.
- BMD test equipment was not widely available as of March 2020, but large contractors tended to have the equipment. Testing labs and medium sized contractors that work in multiple states also had some equipment for the popular BMD tests. Small contractors and labs did not seem to have any equipment. For those organizations that already have BMD test equipment, the makes and models of the equipment are quite diverse.
- Only a few Wisconsin contractors and labs have considerable experience in conducting a complete BMD.
- Although experience with making mix adjustments for BMD is limited, most mix designers indicated that they would likely increase the asphalt content and/or reduce the RAP or RAS content of a mix to improve its cracking resistance. Other possible adjustments cited included using a binder with a lower low-temperature PG or use a recycling agent.
- Strategies suggested to improve the mixture rutting resistance included coarsening the aggregate blend/gradation, increasing angularity of the aggregates, increasing RAP or RAS contents, and using a polymer modified binder.
- There was no consensus on which of the current Superpave volumetric criteria could be eliminated or relaxed for mix designs. A couple of mix designers suggested eliminating fine aggregate angularity and TSR. Views differed on whether air voids and VMA could be eliminated.
- Concerns regarding the implementation of performance testing in mix design and approval range from skepticism about whether BMD would actually result in better quality mixes to

concerns about setting BMD criteria, the demand on DOT manpower, and the feasibility of conducting performance tests during production.

- Interviewers were asked on which types of asphalt mixes should BMD be used. Several commented that BMD should be used on all mixes, while others suggested that the BMD approach be primarily used for overlay projects where a more durable mix is needed to overcome remaining underlying pavement issues. A few also suggested that the decision to use a BMD approach should consider other project-related factors besides traffic levels.

5.1.2 Benchmarking Experiment

- The HWTT CRD_{20k} results of short-term aged specimens varied from 2.7 to 7.7 mm with an average of 4.9 mm. In general, SMA, HT, and MT mixes had lower CRD_{20k} values and thus, were expected to have better rutting resistance than LT mixes. Aggregate NMAS and aggregate type did not seem to have significant impacts on HWTT CRD_{20k} results.
- Three out of the 18 WisDOT mixes did not exhibit a stripping phase in HWTT. The SN results of the other 15 mixes that showed stripping failure ranged from 1,561 to 8,598 passes. In most cases, LT mixes outperformed HT mixes and 12.5 mm mixes outperformed 9.5 mm mixes in terms of moisture resistance in HWTT. Aggregate type was found to affect SN results. In general, granite and quartz mixes had higher SN and thus, were expected to be more resistant to moisture damage than carbonate and gravel mixes.
- The IDEAL-CT CT_{Index} results of long-term aged specimens ranged from 25.4 to 128.1 with an average of 61.2. The highest CT_{Index} value corresponded to the SMA mix. Traffic level had an impact on CT_{Index} results of the Wisconsin mixes, but this impact was mainly attributed to the difference in asphalt binder contents of LT, MT, and HT mixes because of their different N_{design} values. There was no significant difference in CT_{Index} results between the 9.5 mm and 12.5 mm NMAS mixes. Aggregate type was found to impact CT_{Index} results. Granite mixes had the highest CT_{Index} results and thus, are expected to have the best intermediate-temperature cracking resistance followed by carbonate and gravel mixes, and then quartz mixes.
- The DCT G_f results of long-term aged specimens ranged from 292.4 to 555.8 J/m^2, with an average of 367.6 J/m^2. Traffic level did not appear to have a significant impact on G_f results. Despite the wide spread of the G_f results, most of the 12.5 mm NMAS mixes outperformed the 9.5 mm NMAS mixes in the DCT test. Aggregate type was found to have a significant impact on G_f results. Granite mixes had the highest G_f results and thus, are expected to have the best low-temperature cracking resistance followed by quartz mixes, and then carbonate and gravel mixes.

5.1.3 BMD Optimization Experiment

- The strategies used to improve the laboratory mix performance test results were all successful to varying degrees. These strategies include:
    - Add additional asphalt to improve cracking resistance.
    - Remove RAS to improve cracking resistance.

    - Add a rejuvenator to improve cracking resistance.
    - Lower binder low-temperature PG grade to improve cracking resistance.
    - Use a higher MSCR grade binder to improve rutting resistance.
    - Add a liquid anti-strip to reduce moisture susceptibility.
- While LAS marginally improved mixes in the HWTT, the improvement was not enough to achieve a passing HWTT result when used in conjunction with certain binders.
- For a few of the tested mixes, fixing one performance issue created another performance issue. The key word in balanced mix design is ‘balanced.’ The steps taken to fix a cracking problem may create a rutting problem. It is important to recognize this when considering strategies to improve mixture performance test results.
- For a few of the mixes, significant differences in performance test results were found for specimens fabricated by contractors and specimens of the same mix fabricated by NCAT. All specimens for this study were made from lab-mixed, lab-compacted raw materials and tested at NCAT. As agencies move forward with BMD implementation, uniform specimen preparation training and practices along with in-state round-robin studies will be critical to help minimize between-lab differences in performance test results.

5.1.4 Economic Analysis

- The cost analysis indicates that modifications of mixes that failed to meet at least one of the proposed BMD criteria will likely increase the materials cost by approximately 8 to 22%. However, since more than half of the mixes met the proposed BMD criteria, the majority of current Wisconsin mixes will not be affected if the suggested preliminary BMD criteria are implemented.
- Using a rejuvenator and increasing the asphalt content were both effective in improving the intermediate-temperature cracking resistance and could be alternative economic strategies for adjusting mix designs. However, in one case, eliminating RAS was found to be less cost effective than increasing the asphalt content for improving mixture cracking resistance. For asphalt contractors to remain competitive in a low-bid environment, they will need to explore different mix design modification strategies so that they can determine the most cost-effective options for their materials.
- The benchmarking evaluation showed that carbonate and gravel mixes tend to yield lower DCT G_f results. The mix evaluated to improve its DCT results contained carbonate aggregate. The strategy assessed was to use a softer low-temperature grade virgin binder that resulted in improved G_f, but it compromised the mix’s rutting and stripping resistance and therefore, required adding a liquid anti-strip additive. Reducing the carbonate aggregate content could be a potential strategy to improve low-temperature cracking resistance, but further evaluations would be needed to assess its cost-effectiveness.
- One mix was evaluated to improve its rutting and moisture resistance. The selected modification was to use a modified binder with a higher MSCR grade binder and add a liquid anti-strip agent, but these modifications resulted in a 20% cost increase. Other

options to improve rutting and moisture resistance could include changing aggregate type and/or gradation.

- The modification strategies evaluated in this study represent the most intuitive strategies as suggested by mix designers in Wisconsin, but other options driven by a low-bid pavement construction industry should be explored by asphalt contractors to determine the most cost-effective solutions for their materials.

5.2 Recommendations for Future Research

- This project included only one SMA mix in the benchmarking experiment, which is not sufficient to develop robust performance criteria for this mixture type. Therefore, performance testing of additional SMA mixes in Wisconsin is suggested to benchmark their HWTT, IDEAL-CT, and DCT test results.
- Research is needed to validate the suggested preliminary performance test criteria with field performance data. The performance criteria used in a BMD specification should be able to discriminate good-performing and poor-performing mixes in the field.
- Research is needed to evaluate the impact of plant production and production variability on the mixture performance test results for quality assurance of BMD.
- In the BMD optimization experiment, a variety of strategies were evaluated to improve and optimize performance test results for five Wisconsin mixes. Due to limitations of the project, only one or two strategies were evaluated per mix design. More cost-effective solutions may exist for some of these mixes. It would be worthwhile to expand the optimization for a couple of the mix designs.

5.3 Recommendations for Implementation

- Since all five LT mixes in the benchmarking experiment performed well in HWTT, IDEAL-CT, and DCT tests and thus, would be expected to have satisfactory rutting and cracking resistance, WisDOT should consider continuing the current specification with the regressed air voids approach for the design of LT mixes. This would reduce the impact of implementing BMD across the state without sacrificing performance for any Wisconsin roads.
- The MT and HT mixes in the benchmarking experiment showed a wide range of HWTT, IDEAL-CT, and DCT results, which indicates that Wisconsin could be experiencing a broad range of field performance for current asphalt paving mixtures. To better screen out poor performing mixes and improve the performance of asphalt pavements overall, it is recommended that WisDOT implement the Performance-modified Volumetric Design approach for mix design approval and possibly quality assurance testing in the future. This BMD approach will help ensure that MT and HT mixes have satisfactory rutting and cracking resistance while allowing mix designers some innovation potential to meet the performance test requirements. It is also recommended that WisDOT consider using the same BMD approach for SMA mixes but with higher performance test requirements than

those for MT and HT mixes. Suggested modifications to the WisDOT standard specification for the initial implementation of BMD for MT, HT, and SMA mixes are as follows:

  - Replace Table 460-2 in Section 460.2.7 with Table 23, below. Note that the performance criteria suggested for SMA mixes are based on the test results of only one mix in the benchmarking experiment. Thus, benchmarking additional SMA mixes is needed to verify, or adjust if needed, the preliminary criteria for future specification use.
  - Add a new section 460.2.4.5, Recycling Agents to read, “Recycling agents may be used to help meet the performance test requirements of MT, HT, SMA mixes containing high RAP and/or RAS materials.”

- The following activities are recommended for WisDOT to move forward with the implementation of mixture performance tests for BMD:
  - Notify asphalt contractors of plans to implement HWTT, IDEAL-CT, and possibly the DCT test.
  - Conduct training on sample preparation and mixture performance testing.
  - Continue to collect mixture performance test results for WisDOT mixes.
  - Construct BMD shadow projects for MT, HT, and SMA mixes.
  - Analyze test results from the BMD shadow projects to quantify production variability on the mixture performance test results.
  - Monitor the field performance of BMD shadow projects.
  - Set a strategy for the implementation of mixture performance tests for Quality Assurance.
  - Develop a provisional BMD specification and construct pilot projects.

Table 23. Suggested Changes (highlighted in red) to Table 460-2 of the WisDOT Standard Specification

Mixture Type	LT	MT	HT	SMA
LA Wear (AASHTO T96)				
100 revolution (max % loss)	13	13[12]	13[12]	13[12]
500 revolution (max % loss)	50	45[12]	45[12]	35[12]
Soundness (AASHTO T104) (sodium sulfate, max % loss)	12	12[12]	12[12]	12[12]
Freeze/Thaw (AASHTO T103 as modified in CMM 860.2) (specified counties, max % loss)	65/__	75/60[12]	98/90[12]	100/90[12]
Flat & Elongated (ASTM D4791) (max %, by weight)	5 (5:1 ratio)	5[12] (5:1 ratio)	5[12] (5:1 ratio)	20[12] (3:1 ratio)
Fine Aggregate Angularity (AASHTO T304, method A, min)	40[1]	43[1][12]	45[12]	45[12]
Sand Equivalency (AASHTO T176, min)	40	40[2][12]	45[12]	50[12]
Clay Lumps and Friable Particle in Aggregate (AASHTO T112)	≤ 1%	≤ 1%[12]	≤ 1%[12]	≤ 1%[12]
Plasticity Index of Material Added to Mix Design as Mineral Filler (AASHTO T89/90)	≤ 4	≤ 4[12]	≤ 4[12]	≤ 4[12]
Gyratory Compaction				
~~Gyrations for N_{ini}~~	~~6~~	~~7~~	~~8~~	~~7~~
Gyrations for N_{des}	40	75	100	65
~~Gyrations for N_{max}~~	~~60~~	~~115~~	~~160~~	~~100~~
Air Voids, %Va (%G_{mm} N_{des})	4.0 (96.0)	2.0-4.0 (96.0-98.0)	2.0-4.0 (96.0-98.0)	3.0-4.5 (95.5-97.0)
~~%G_{mm} N_{ini}~~	~~≤ 91.5[3]~~	~~≤ 89.0[3]~~	~~≤ 89.0~~	-
~~%G_{mm} N_{max}~~	~~≤ 98.0~~	~~≤ 98.0~~	~~≤ 98.0~~	~~≤ 98.0~~
Dust to Binder Ratio[4] (% passing 0.075/P_{be})	0.6-1.2[5]	0.6-1.2[5]	0.6-1.2[5]	1.2-2.0
Voids filled with Binder (VFB or VFA, %)	68-80[6][8]	65-88[6][7][9]	65-88[6][7][9]	70-89
Hamburg Wheel Tracking Test (HWTT) (AASHTO T324) at 46°C[13]	-			
Corrected Rut Depth (CRD_{20k}, mm)		≤ 7.0	≤ 6.0	≤ 6.0
Stripping Number (SN, passes)		≥ 2,000	≥ 2,000	≥ 2,000
Indirect Tensile Asphalt Cracking Test (IDEAL-CT) (ASTM D8225) at 25°C[14] Cracking Tolerance Index (CT_{Index})	-	≥ 40	≥ 40	≥ 80
Disc-shaped Compact Tension Test (DCT, ASTM D7313) at 10°C above the low-temperature grade in the contract plans[14] Fracture Energy (G_f, J/m^2)	-	≥ 300	≥ 300	≥ 400
Tensile Strength Ratio (TSR) (AASHTO T283)[10][11]				
no antistripping additive	0.75 min	0.75 min[15]	0.75 min[15]	0.80 min[15]
with antistripping additive	0.80 min	0.80 min[15]	0.80 min[15]	0.80 min[15]
Draindown (AASHTO T305) (%)	-	-	-	≤ 0.30
Minimum Effective Asphalt Content, P_{be} (%)	-	-	-	5.5

[1] For No 6 (4.75 mm) nominal maximum size mixes, the specified fine aggregate angularity is 43 for LT mixes and 45 for MT mixes.

[2] For No 6 (4.75 mm) nominal maximum size mixes, the specified sand equivalency is 43 for MT mixes.

[3] The percent maximum density at initial compaction is only a guideline.

[4] For a gradation that passes below the boundaries of the caution zone (ref. AASHTO M323), the dust to binder ratio limits are 0.6 - 1.6.

[5] For No 6 (4.75 mm) nominal maximum size mixes, the specified dust to binder ratio limits are 1.0 - 2.0 for LT mixes and 1.5 - 2.0 for MT and HT mixes.

[6] For No. 6 (4.75mm) nominal maximum size mixes, the specified VFB is 67 - 79 percent for LT mixes and 66 - 77 percent for MT and HT mixes.

[7] For No. 5 (9.5mm) and No. 4 (12.5 mm) nominal maximum size mixtures, the specified VFB range is 70 - 76 percent.

[8] For No. 2 (25.0mm) nominal maximum size mixes, the specified VFB lower limit is 67 percent.

[9] For No. 1 (37.5mm) nominal maximum size mixes, the specified VFB lower limit is 67 percent.

[10] WisDOT eliminates freeze-thaw conditioning cycles from the TSR test procedure.

[11] Run TSR at asphalt content corresponding to 3.0% air void regressed design for LT mixes~~, or 4.5% air void design for SMA~~, using distilled water for testing.

[12] The aggregate properties are for guidelines only.

[13] Run HWTT on specimens that have been short-term aged for 4 hours at 135°C prior to compaction.

[14] Run IDEAL-CT and DCT on specimens that have been short-term aged for 4 hours at 135°C and then long-term aged for 6 hours at 135°C prior to compaction.

[15] TSR testing is only required when the mix fails the HWTT *SN* criterion.

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APPENDIX A. INTERVIEWS OF ASPHALT MIX DESIGNERS REGARDING BMD IMPLEMENTATION AND SPECIFICATION LIMITS

Seven experienced Wisconsin mix designers were interviewed and asked 15 questions related to BMD. The group included representatives of large and small contractors and consulting/testing labs. The identities of the interviewees are not disclosed and only identified by a letter to preserve their anonymity.

1. How many years of experience with asphalt mix design do you have?

Interviewee	Years of Mix Design Experience
A	10
B	22
C	20
D	30
E	5
F	10
G	6

Conclusion: this group of mix designers are well qualified.

2. How many asphalt plants do you have?

A: We don’t own asphalt plants; I operate a contracting lab for customer support and through this service I have done designs for approx. 10 unique plants.
B: My company currently owns 5 plants with regular day to day operations out of 4 of those plants.
C: None. I am a consultant.
D: None. We are a testing lab.
E: Approximately 40 in multiple states.
F: 4 plants
G: Number of plants is not relevant. My company operates in multiple states. We deal with aggregates of varying mineralogy.

Conclusion: The group included consulting labs, small and large contractors.

3. How many mix designs do you typically do in a year for the following categories?

A: Total = 10, SMA = 0, High Traffic = 0, Med. Traffic = 5, Low Traffic = 5

B: Total = 7-12, SMA = 0-2, High Traffic = 1-2, Med. Traffic = 3-4, Low Traffic = 3-4

C: Total = 6, SMA = 0, High Traffic = 0, Med. Traffic = 3, Low Traffic = 3

D: Total = 5, SMA = 0, High Traffic = 0, Med. Traffic = 5, Low Traffic = 0

E: Total = 130, SMA = 5, High Traffic = 15, Med. Traffic = 60, Low Traffic = 60

F: Total = 6-9, SMA = 0-1, High Traffic = 2, Med. Traffic = 2-4, Low Traffic = 4

G: Again specific number is not relevant. There are normally a few SMA projects per year. We do plenty of dense graded mixes across the company. Primarily MT or LT, HT is also used.

Conclusion: The vast majority of mix designs in Wisconsin are for medium and low traffic projects. Based on the responses, it appears that about half of all mix designs are in the MT category and about 40% are in the LT category.

4. What grades of virgin binders do you use in your designs?

A: PG58S-28; PG58H-28, PG58S-34; vast majority is PG58S-28
B: Most often we utilize 58-28S, with 58-28H and lastly 58-28V
C: Most Wisconsin contractors use 58-28S or V binders for state projects. PG 64-22 for private projects that do not require PG specification (cheapest binder on the market)
D: PG 58-28S
E: Mostly PG 58-28, sometimes PG 58-34
F: 58-28
G: PG 58S-28 or in some cases PG 52S-34 (to accommodate the use of more RAM)

Conclusion: The most used binder grade in Wisconsin is PG 58S-28.

5. Do you use recycled asphalt singles (RAS) in your mix designs? If yes, are they manufacturing waste or tear-off asphalt shingles?

A: Yes; Manufacturer Waste; 1 plant
B: We typically run RAP or FRAP only designs, but when we do run RAS in a limited capacity they are from tear off shingle sources.
C: No (but when I worked for a contractor, I would)
D: No shingles.
E: Yes, we use both.
F: Yes, tear-off
G: Yes, in some areas, and they are tear-off

Conclusion: Most Wisconsin contractors use RAS. Both manufacturer waste and post-consumer RAS are used, but post-consumer RAS is more common.

6. Does your laboratory have test equipment available for conducting the following performance tests? If yes, how many and what equipment brand are they?

- HWTT

  A: No, Outsource
  B: We have a Troxler small (EWTM) HWT and a Controls DWT unit as well.
  C: PMW
  D: No
  E: Troxler PMW and Instrotek SmarTracker
  F: None

G: PMW

- IDEAL-CT

A: Yes; Karol Warner 10K load frame and controller.
B: Yes, Testquip.
C: No
D: No
E: Yes, three Instrotek
F: Considering getting Troxler device
G: Yes

- I-FIT

A: No, Outsource
B: Yes, Testquip
C: Yes, Brovold (Testquip)
D: No
E: Yes, UTM, Controls
F: No
G Yes, Instron UTM

- DCT

A: No, Outsource
B: We have two Testquip units one with an attached IDEAL-CT apparatus and one that could be utilized as a standalone.
C: Yes, Brovold (Testquip)
D: No
E: Yes, UTM, Controls
F: No
G: Yes, Instron UTM

Conclusion: At this time, BMD test equipment is not widely available. Large contractors tend to have the equipment. Testing labs and medium sized contractors that work in multiple states also have some equipment for the popular BMD tests. Small contractors and labs may not have any equipment. For those organizations that already have equipment, the makes and models of the equipment is quite diverse.

7. What's your level of experience with performance specimen fabrication and testing?

A: High; have done research work for WHRP and Private on performance testing.
B: We are very proficient at preparing and cutting specimens for both the DCT and I-FIT tests as we have been testing for projects in another state for quite some time. We have also become proficient at fabricating the IDEAL CT specimens as well per the latest WHRP study. In addition, we will send you a city specification as

they are progressive with their performance specs and much closer to a BMD type structure although, not fully there yet. We have been utilizing this spec since 2016, so we are very familiar with both preparing and running the DCT, IFIT and Hamburg tests.

C: Very high. We do a lot of performance testing for other contractors, and for research.

D: None

E: 15 years

F: No practical experience. Other organizations prepare the specimens for us.

G: High, the first project with performance testing was 2014. Hamburg, DCT, SCB, were all used.

Conclusion: At this time, experience in preparing mix specimens for the popular BMD tests is mixed.

8. What's your level of experience conducting a BMD?

A: Low; I have personally just researched/conducted individual test methods, designs, not the full BMD process or adjustments to designs.

B: As mentioned above, we have performed the "Volumetric Design with Performance Verification" method for a city since 2016.

C: We review BMD and write specs for BMD for the Illinois Tollway. Illinois Tollway: Volumetric Design with Performance Verification + testing on recovered binder from loose mix (PG and delta Tc)

D: No experience

E: Minimum, ~ 2 years.

F: No practical experience

G: Understand all three levels. Have only run Level 1 on projects.

Conclusion: At this time, only a few Wisconsin contractors and labs have much experience in conducting a complete BMD.

9. If your mix design fails the cracking test requirement, what is your most preferred method for design modification?

A: Likely adjust binder content up and/or recycled binder ratio down.

B: We are currently doing research to answer that very question in regards to the IDEAL-CT. As for the IFIT and DCT, both aggregate source and RAP/RAS percentages changes have been made with some success. When allowed, a softer binder grade has a positive effect, and the possible use of a rejuvenator/WMA additive as well.

C: First – check Dust to Binder (film thickness), and possibly add more binder. Then, look at binder grade and amount of RAS or FRAP in a mix design, possibly soften the lower end PG Grade. You could also look at rejuvenators – we have evaluated these for supplier clients (Illinois Tollway evaluates rejuvenator by supplier; if a product shows improved results based on performance testing, then it will be used on the shoulder for performance monitoring. Illinois Tollway has a list of approved rejuvenator products.). Lastly, you can look at agg source and quality of aggregates.

D: N/A

E: More asphalt

F: No experience, but probably to reduce recycled content, increase Veff.

G: Keep high temperature grade the same and use colder LT PG grade. For example PG 58S-28 would go to PG 58S-34.

Conclusion: Although experience is limited in making mix adjustments at this time, most mix designers say that they would likely increase the asphalt content and or reduce the RAP or RAS content of a mix to improve its cracking resistance. Other possible adjustments cited included using a binder with a lower low PG or use a rejuvenator.

10. If your mix design fails the rutting test requirement, what is your most preferred method for design modification?

A: If OK on cracking, stiffen by increase RAP.

B: Increasing the fractured stone and or sand content, if possible, or if we are not at the max ABR (Asphalt Binder Replacement) tolerance, adding RAS/RAP/FRAP could help depending on Volumetric data.

C: When a mixture ruts, it may have to do with whether it was designed on the fine side or the coarse side. The fine mixtures have a tendency to show more rutting (however I don’t necessarily think they rut as much as the HWT would indicate). I like that WisDOT lowered the temperature of the spec – I think that helps calibrate the machine to a finer mix. Otherwise – on coarse graded mixtures or SMAs one way to decrease rutting is to improve the aggregate quality (use quartzite or high Sp. Gr. stone) or add FRAP and/or RAS.

D: N/A

E: More angular aggregates

F: Change aggregate structure.

G: Change aggregate blend or use modified binder. Depends on circumstances.

Conclusion: Most Wisconsin mix designers would coarsen the aggregate blend/gradation and/or increase angularity of the aggregates to improve rutting test results. Other possible adjustments would include increasing RAP or RAS contents and using a modified binder.

11. Based on your understanding of the three BMD approaches, which one do you prefer? For convenience, these approaches are briefly discussed and schematically illustrated on the flowchart in Figure 1 included at the end of this questionnaire.

A: Approach 2 until we (as an industry) can trust the performance tests to simulate actual field conditions. I view Approach 2 as a smoother transition since there will be some history to the designs being used.

B: Ideally the “Performance Design” method would be the most prudent, but it is unlikely agencies will be willing to accept this method anytime soon. In lieu of that, the “Performance Modified Volumetric Design” Method would be our next choice.

C: I like the Volumetric design with Performance Verification. Why mess with something we know (Volumetrics)? I think we are at a place where we can use performance tests to help improve our mixtures. I don’t think we are ready to just believe all performance tests as gospel. Let’s take the conservative approach.

D: Probably 1 or 2. Volumetrics will likely still be important during production.

E: Approach 3

F: 2.5? some volumetric criteria for quality control.

G: If I had to pick my preference would be for Approach 2. I don’t see much value in Approach 1 and agencies are very hesitant to implement Approach 3 particularly with the uncertainty associated with many of these tests.

Conclusion: Although responses favored all three options, most mix designers suggest starting with Approach 2 until further confidence is gained with the BMD tests.

12. What do you think is a practical amount of time to complete a BMD?

A: 3 working weeks from receipt of aggregate to final report.

B: Eight days would be a reasonable amount of time to finish a full Balance Mix Design with performance testing. That number would also hinge on the Long term aging protocol selected.

C: From starting with aggregates and having to create a blend – then run performance tests? 6 to 8 weeks. It would probably take us longer because our clients always bring in new aggregate with no history. What about modifying an existing design to pass BMD performance criteria? 1 to 2 weeks

D: Unknown

E: 3 weeks

F: 2 weeks will be ideal.

G: Approximately as long as a normal mix design. If the time frame is extended, the value added to the design needs to be understood.

Conclusion: Responses ranged from as short as 8 days to as long as 8 weeks. This broad range in the expected time likely depends on whether or not a volumetric mix design already exists for the set of materials.

13. What are your concerns regarding the implementation of performance testing in mix

design and approval?

A: Adjusting away from trusted designs & materials because an unproven (or yet to be vetted) lab test dictates an adjustment; variability of test method – for QA/QV purposes; sensitivity of the test to known mix design factors appears to be lacking – are we totally fooling ourselves with the applicability of these tests.

B: Our biggest concern would be choosing a threshold number for any of the tests that would drastically change the current mix design makeup. I believe that our regressed fine graded mixtures are superior to the coarse graded mixtures that we are forced to run in Illinois, notwithstanding SMA that is. Also comparing with other agencies would be a concern. The procedures would have to be followed closely between two different labs/personnel/machines. If the same procedure isn't followed exactly, we have had issues with comparing where small differences in protocol seem to have made quite a difference in results.

C: DOT needs to verify mix design but may not have enough manpower and test equipment available. An alternative would be to check performance (verify mix design) on test strip.

D: Over reliance on the new method before it's proven itself. How will quality control be performed during production?

E: That volumetric criteria may not be relaxed, and you will just be adding tests to conduct during mix design.

F: Passing and failing criteria of the tests.

G:

- How were the initial performance thresholds determined? How will acceptance thresholds be determined?
- What types of designs will be impacted? Gearing up for implementation with equipment and staff training.
- What value is the IDEAL CT test if there is the same performance threshold across all three traffic levels?
- Why does the IDEAL CT test show opposite effects with respect to air voids and modification?
- DCT test temperature should be selected based on climate PG temperature, not the virgin binder grade.
- General concerns about how useful the IDEAL CT test is as a design tool. It adds more value as a test that can compare design vs. production.
- What will tolerances be?
- Will this be used during production? Will design need to consider production tolerances?
- Concerns related to rutting derived from an extrapolation. Why not direct measurement such as dry Hamburg or AMPT stress sweep?

Conclusion: Responses to this question touched on a range of concerns from skepticism about whether BMD would actually result in better mixtures, concerns about setting BMD criteria, the demand on DOT manpower, and the impact on testing during production.

14. Which existing volumetric mix design criteria do you think could be relaxed or eliminated without sacrificing performance?

A: I think the current volumetric specification with air void regression, lower gyration numbers, and higher VMA is producing a pretty good mix. To me the 2 biggest issues are (1) accurately measuring and enforcing accurate Gsb values for our aggregate, which in turn inflates VMA, (2a) tracking RAS usage and contribution in the mixtures, and (2b) the method used to calculate percent binder replacement needs to be updated.

B: I believe TSR testing could be dropped as there has been a multitude of TSR Testing completed on Wisconsin mixes with very few failures, especially since the addition of the regressed air void specification (0.4 - 0.5% more AC). The fact that the S.I.P. can be analyzed within the Hamburg data would help support dropping the TSR test as well.

C: %Gmm at Nini and Nmax – eliminated. Air Voids and VMA – No change

D: Unknown

E: FAA, Air voids, VMA.

F: FAA, DP, all consensus properties (relaxed)

G: VFA can be eliminated. Reconsider TSR if Hamburg SIP is being used. This whole process is a bit convoluted considering air void regression is already in place. Air void ranges during production were already changed.

Conclusion: There was no consensus on which current criteria could be eliminated for mix designs. A couple of mix designers suggested eliminating fine aggregate angularity and TSR. Views differed on whether or not air voids and VMA could be eliminated.

15. On which types of asphalt mixes do you think WisDOT should use a BMD approach?

A: My opinion is that it should not be limited to a certain type, but rather a desired degree of "reliability" in the paving job and where the mixtures will be used (overlay, mill/fill, new construction, etc.) – not all "LT", "MT", and "HT" mixtures are created equal – cracking resistance for an overlay *probably* needs to be greater than a similar mix used in new construction not exposed to reflective type stresses. Similarly, I believe there are some jobs where ancillary costs – closing traffic, etc. – are more critical. These jobs should have that added layer of reliability. For your average county trunk highway MT mix, I'm not sure the costs are justified for performance testing until the industry gets a familiarity and trust with the process.

B: Any mix that would be used for an overlay project. We think the agency should be interested in a “flexible” pavement that can bridge some of harsh underlying conditions we have been encountering lately. We believe that the BMD approach, with its emphasis on performance testing in addition to volumetrics would be instrumental in achieving that goal.

C: BMD can be used on all mixes, but may want to start on SMA, HT, and possibly MT mixes, and keep using regressed air voids for LT mixes.

D: No opinion

E: Not mix specific, but type of construction, overlay, mill/fill? For example if a 2inches mill and fill is needed, is BMD required?

F: All

G: That is a decision for WisDOT

Conclusion: The mix designers offered different viewpoints on this question. Several commented that BMD should be used on all mixes, while others suggested that the BMD approach be primarily used for overlay projects where a more durable mix is needed to overcome remaining underlying pavement issues. A few also suggest that the decision to use a BMD approach should consider other project related factors besides traffic levels.

APPENDIX B. NCAT SPECIMEN FABRICATION PROCEDURE FOR BENCHMARKING EXPERIMENT

Instructions for Fabricating Hamburg Specimens

- NCAT will need five (5) – 62 mm tall specimens prepared to 7.0 ± 0.5 percent air voids for Hamburg testing. Specific instructions for specimen fabrication and aging are below.
- First, you will need to know an approximate trial mass for these specimens to know how much material to batch per specimen.
    - You will need the G_{mm} of the mixture at the desired asphalt content.
        - This value may be obtained from the JMF if the design has been recently verified. Otherwise, it is recommended you batch separate specimens and update this value.
    - Using the provided spreadsheet 'Trial Mix Weights – NCAT, go to the 'Initial Gyratory Weights' tab and enter the JMF Rice (G_{mm}) value in cell B1.
    - The Sample Height for these specimens should be 62 mm and the Target Air Voids should be 7.0%.
    - Cell 'B8' will give you your best estimate of a starting mix weight.
    - The batch weights should yield at minimum this amount of mix (and likely an extra 100 to 200 grams as a factor of safety).
    - It is recommended to batch a minimum of 18 samples at this mass. These batches will include the ones needed for IDEAL-CT testing later (though those specimens will be aged differently) in addition to a trial sample and a rice verification.
    - Batch the specimens in accordance with your own laboratory procedures and best practices.
- After mixing, the Hamburg specimens will be short-term oven aged for 4 hours at 275°F using the short-term mechanical aging procedure found in AASHTO R30-02 (2015) – Section 7.2.
    - The mix should be aged in pans at an even thickness of 1" to 2" thick and stirred every hour, per R30.
    - The Hamburg samples will be compacted after the short-term oven aging (no critical oven aging).
- It is recommended to mix one trial sample by itself to verify the required mass in the mold along with verifying the G_{mm}.
    - Mix three specimens and compact one specimen using the aging procedures outlined above.
        - One specimen will be compacted for a trial weight.
        - The other two specimens can be kept loose and broken up to verify the G_{mm}.
    - The height of the specimen will be 62 mm and the mass of mix in the mold will be the value calculated from the Trial Mix Weights Spreadsheet (discussed under determining the appropriate batch weight).
    - Allow the specimen to cool completely and then determine the bulk specific gravity and calculate air voids.

  - The ‘Solve for Mix Weight – 1 Sample’ tab in the Trial Mix Weights Spreadsheet can now be used to calibrate the target mass in the mold.
    - Input the mass of the compacted trial sample (Cell B3)
    - Input the calculated air voids of the trial sample (Cell B4)
      - Use the verified G_{mm} value for the air voids calculation.
    - The Target Air Voids of the Sample should be 7.0 for 62 mm samples.
    - The new mass in the mold is shown in Cell B7. This will be the mass at which you compact your next round of samples.
      - Disclaimer: The correction in this spreadsheet is intended to make small air void corrections only. If the air voids of your trial sample is between 6.2 and 7.8 percent air voids, you can likely use the corrected mass and proceed to fabricating your main group of samples. If your trial specimen is outside this range, we recommend you perform another trial to calibrate the weight.
- One you have determined the appropriate mass in the mold to yield 7.0 ± 0.5 percent air voids, proceed to fabricating the remainder of the specimens. We will need 5 Hamburg specimens that meet this tolerance for testing (including one extra).

Instructions for Fabricating IDEAL-CT Specimens

- NCAT will need five (5) – 62 mm tall specimens prepared to 7.0 ± 0.5 percent air voids for IDEAL-CT testing. Specific instructions for specimen fabrication and aging are below.
- Specimen batching for IDEAL-CT specimens is the same as discussed for the Hamburg specimens.
- After mixing, the IDEAL-CT specimens will first be short-term oven aged for 4 hours at 275°F using the short-term mechanical aging procedure found in AASHTO R30-02 (2015) – Section 7.2.
  - The mix should be aged in pans at an even thickness of 1” to 2” thick and stirred every hour, per R30.
- After short-term oven aging, the loose mixture will then be ‘critically’ (long-term) oven aged for 6 hours at 275°F. A summary of the procedure follows…
  - Transfer the loose mixture into a large pan for critical aging and separate into a loose state - similarly as for Rice specific gravity samples.
  - NCAT uses half sheet pans that measure 17”x 25” x 1” deep and we place about 2,500-2,700 grams of mixture on each pan.
  - The important step is that the mix is placed in a thin layer (no more than ¾” – 1” thick) to promote air flow.
    - Different pans may be used to perform critical aging so long as the asphalt mixture is spread in a thin layer. The mass of material may vary depending on the type of pan used.
    - If you are using different sized pans, an easy way to calculate the mass required (in grams) is to measure the area (length x width) and multiply by 6.25. Bear in mind this is an approximate value.
  - The mixes may be short-term aged one day, spread out on pans, and critically aged the next day. A timer on a larger oven would be required to start the 6 hours of aging overnight.
- After the critical aging of 6 hours at 275°F, transfer the loose mixtures to small pans and heat them to the compaction temperature. Proceed to compaction when the mixes have reached the appropriate temperature.
  - If the compaction temperature of the mix is 280°F or less, we recommend proceeding straight to compaction after critical aging.
- Compact the specimens after the mixture temperature reaching the compaction temperature.
- It is recommended to mix one trial sample by itself to verify the required mass in the mold along with verifying the G_{mm}.
  - Mix three specimens and compact one specimen using the aging procedures outlined above.
    - One specimen will be compacted for a trial weight.
    - The other two specimens can be kept loose and broken up to verify the G_{mm}.

            - It is recommended to verify the G_{mm} after critical aging and use this value to calculate the air voids of the IDEAL-CT specimens.
    - The height of the specimen will be 62 mm and the mass of mix in the mold will be the value calculated from the Trial Mix Weights Spreadsheet.
    - Allow the specimen to cool completely and then determine the bulk specific gravity and calculate air voids.
    - The ‘Solve for Mix Weight – 1 Sample’ tab in the Trial Mix Weights Spreadsheet can now be used to calibrate the target mass in the mold.
        - Input the mass of the trial sample (Cell B3)
        - Input the calculated air voids of the trial sample (Cell B4)
            - Use the verified critically aged G_{mm} for the air voids calculation
        - The Target Air Voids of the Sample should be 7.0 for 62 mm samples.
        - The new mass in the mold is shown in Cell B7. This will be the mass at which you compact your next round of samples.
            - Disclaimer: The correction in this spreadsheet is intended to make small air void corrections only. If the air voids of your trial sample is between 6.2 and 7.8 percent air voids, you can likely use the corrected mass and proceed to fabricating your main group of samples. If your trial specimen is outside this range, we recommend you perform another trial to calibrate the weight.
- One you have determined the appropriate mass in the mold to yield 7.0 ± 0.5 percent air voids, proceed to fabricating the remainder of the specimens. We will need 5 IDEAL-CT specimens that hit this tolerance for testing.

Instructions for Fabricating DCT Specimens

- NCAT will need four (4) – 160 mm tall specimens prepared to between 7.4 and 8.0 percent air voids for DCT testing. Specific instructions for specimen fabrication and aging are below.
- First, you will need to know an approximate trial mass for these specimens to know how much material to batch per specimen.
    - You will need the G_{mm} of the mixture at the desired asphalt content.
        - This value may be obtained from the JMF if the design has been recently verified. Otherwise, it is recommended you batch separate specimens and update this value.
    - Using the provided spreadsheet ‘Trial Mix Weights – NCAT, go to the ‘Initial Gyratory Weights’ tab and enter the JMF Rice (G_{mm}) value in cell B1.
    - The Sample Height for these specimens should be 160 mm and the Target Air Voids should be 7.6%.
    - Cell ‘B8’ will give you your best estimate of a starting mix weight.
    - The batch weights should yield at minimum this amount of mix (and likely an extra 100 to 200 grams as a factor of safety).
    - It is recommended to batch a minimum of 6 samples at this mass.

  - Batch the specimens in accordance with your own laboratory procedures and best practices.
- After mixing, the DCT specimens will first be short-term oven aged for 4 hours at 275°F using the short-term mechanical aging procedure found in AASHTO R30-02 (2015) – Section 7.2.
  - The mix should be aged in pans at an even thickness of 1” to 2” thick and stirred every hour, per R30.
    - Multiple pans may be required per specimen to have the mix at the correct thickness.
- After short-term oven aging, the loose mixture will then be ‘critically’ (long-term) oven aged for 6 hours at 275°F. A summary of the procedure follows…
  - Transfer the loose mixture into a large pan for critical aging and separate into a loose state - similarly as for Rice specific gravity samples.
  - NCAT uses half sheet pans that measure 17”x 25” x 1” deep and we place about 2,500-2,700 grams of mixture on each pan.
  - The important step is that the mix is placed in a thin layer (no more than ¾” – 1” thick) to promote air flow.
    - Different pans may be used to perform critical aging so long as the asphalt mixture is spread in a thin layer. The mass of material may vary depending on the type of pan used.
    - If you are using different sized pans, an easy way to calculate the mass required (in grams) is to measure the area (length x width) and multiply by 6.25. Bear in mind this is an approximate value.
  - The mixes may be short-term aged one day, spread out on pans, and critically aged the next day. A timer on a larger oven would be required to start the 6 hours of aging overnight.
- After the critical aging of 6 hours at 275°F, transfer the loose mixtures to small pans and heat them to the compaction temperature. Proceed to compaction when the mixes have reached the appropriate temperature.
  - If the compaction temperature of the mix is 280°F or less, we recommend proceeding straight to compaction after critical aging.
- Compact the specimens after the mixture temperature reaching the compaction temperature.
- It is recommended to mix one trial sample by itself to verify the required mass in the mold.
  - Use the G_{mm} after critical aging to calculate air voids (discussed under the IDEAL-CT instructions).
  - The height of the specimen will be 160 mm and the mass of mix in the mold will be the value calculated from the Trial Mix Weights Spreadsheet.
  - Allow the specimen to cool completely and then determine the bulk specific gravity and calculate air voids.
  - The ‘Solve for Mix Weight – 1 Sample’ tab in the Trial Mix Weights Spreadsheet can now be used to calibrate the target mass in the mold.

        - Input the mass of the trial sample (Cell B3)
        - Input the calculated air voids of the trial sample (Cell B4)
        - The Target Air Voids of the Sample should be 7.6 for 160 mm samples.
        - The new mass in the mold is shown in Cell B7. This will be the mass at which you compact your next round of samples.
            - Disclaimer: The correction in this spreadsheet is intended to make small air void corrections only. If the air voids of your trial sample is between 7.0 and 8.0 percent air voids, you can likely use the corrected mass and proceed to fabricating your main group of samples. If your trial specimen is outside this range, we recommend you perform another trial to calibrate the weight.
- One you have determined the appropriate mass in the mold to yield between 7.4 and 8.0 percent air voids on the 160 mm samples, proceed to fabricating the remainder of the specimens. We will need 4 160 mm specimens that hit this tolerance for DCT testing.

APPENDIX C. BENCHMARKING DATA ANALYSIS OF TRADITIONAL HWTT PARAMETERS

Rutting Parameter – Passes to 12.5 mm Rut Depth ($N_{12.5}$)

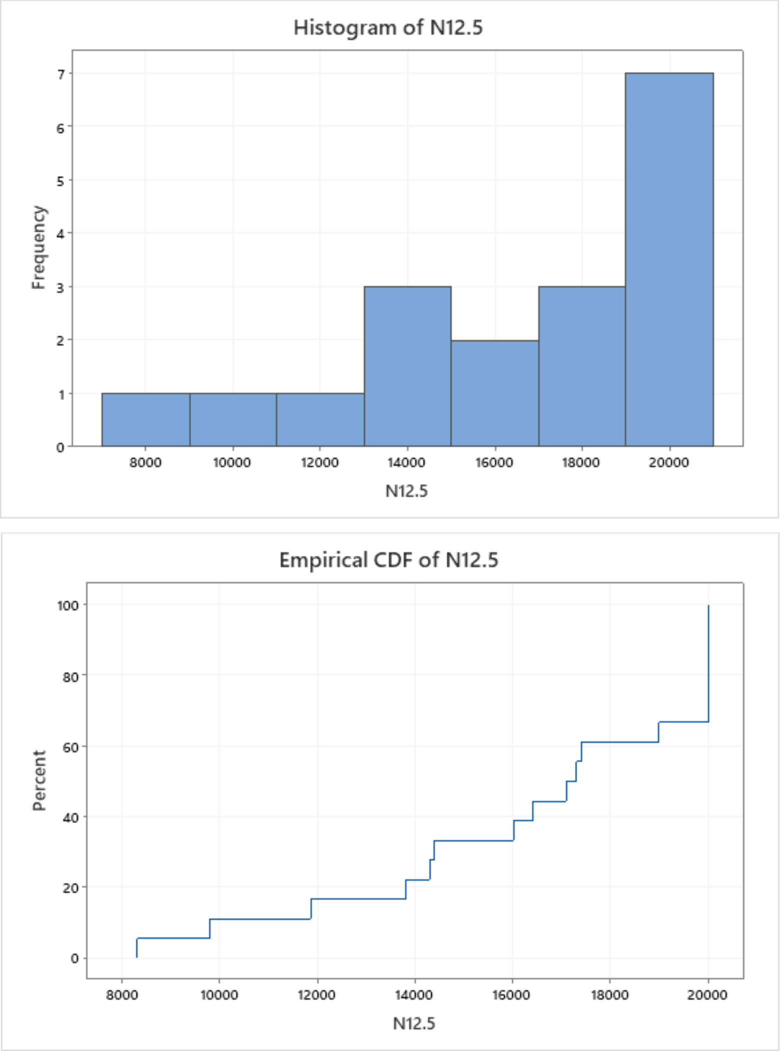

Figure C1. HWTT $N_{12.5}$ Results at 46°C (a) Histogram, (b) Cumulative Distribution Curve

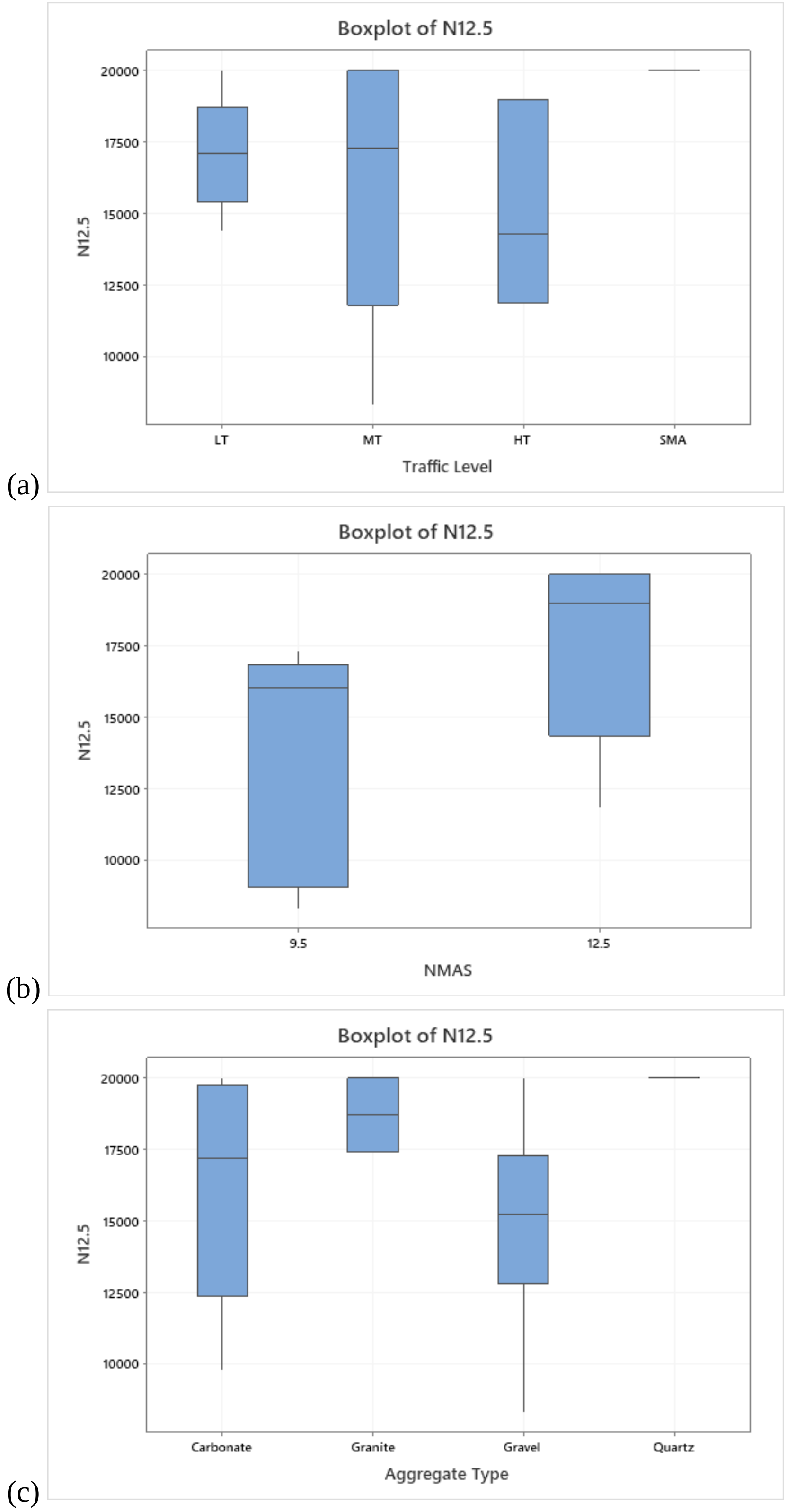

Figure C2. Boxplots of HWTT $N_{12.5}$ Results at 46°C by (a) Traffic Level, (b) Aggregate NMAS, and (c) Aggregate Type

Moisture Damage Parameter – Stripping Inflection Point (SIP)

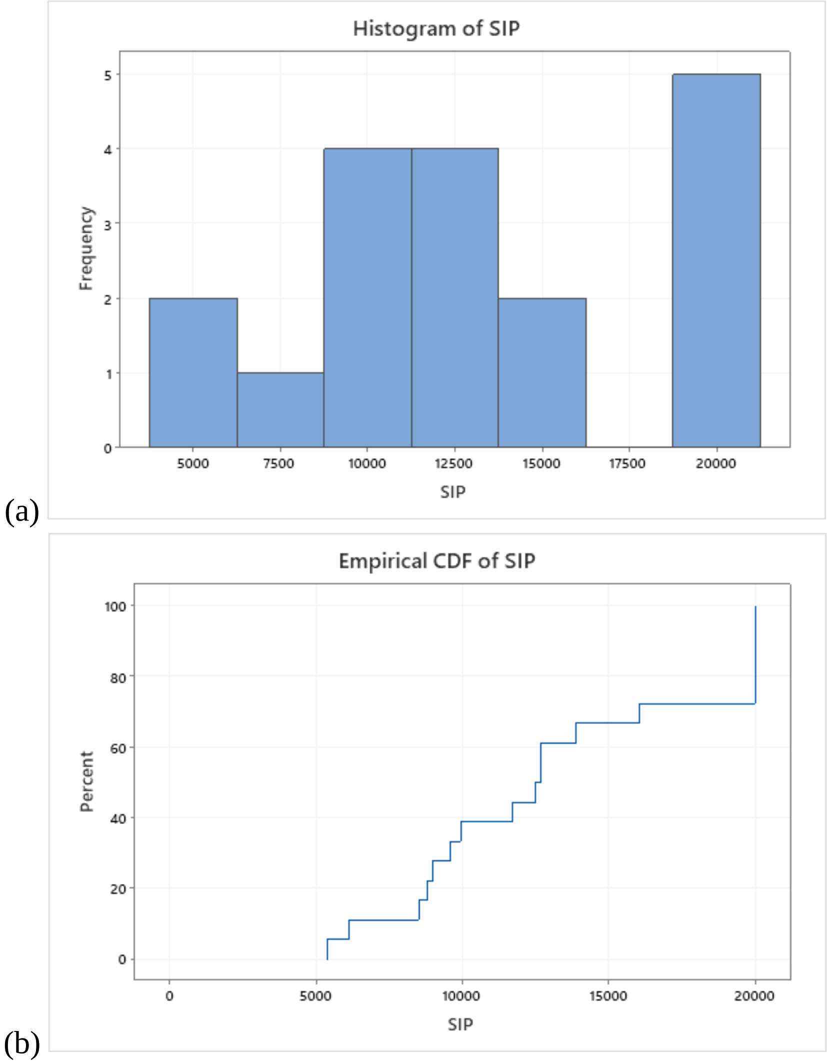

Figure C3. HWTT *SIP* Results at 46°C (a) Histogram, (b) Cumulative Distribution Curve

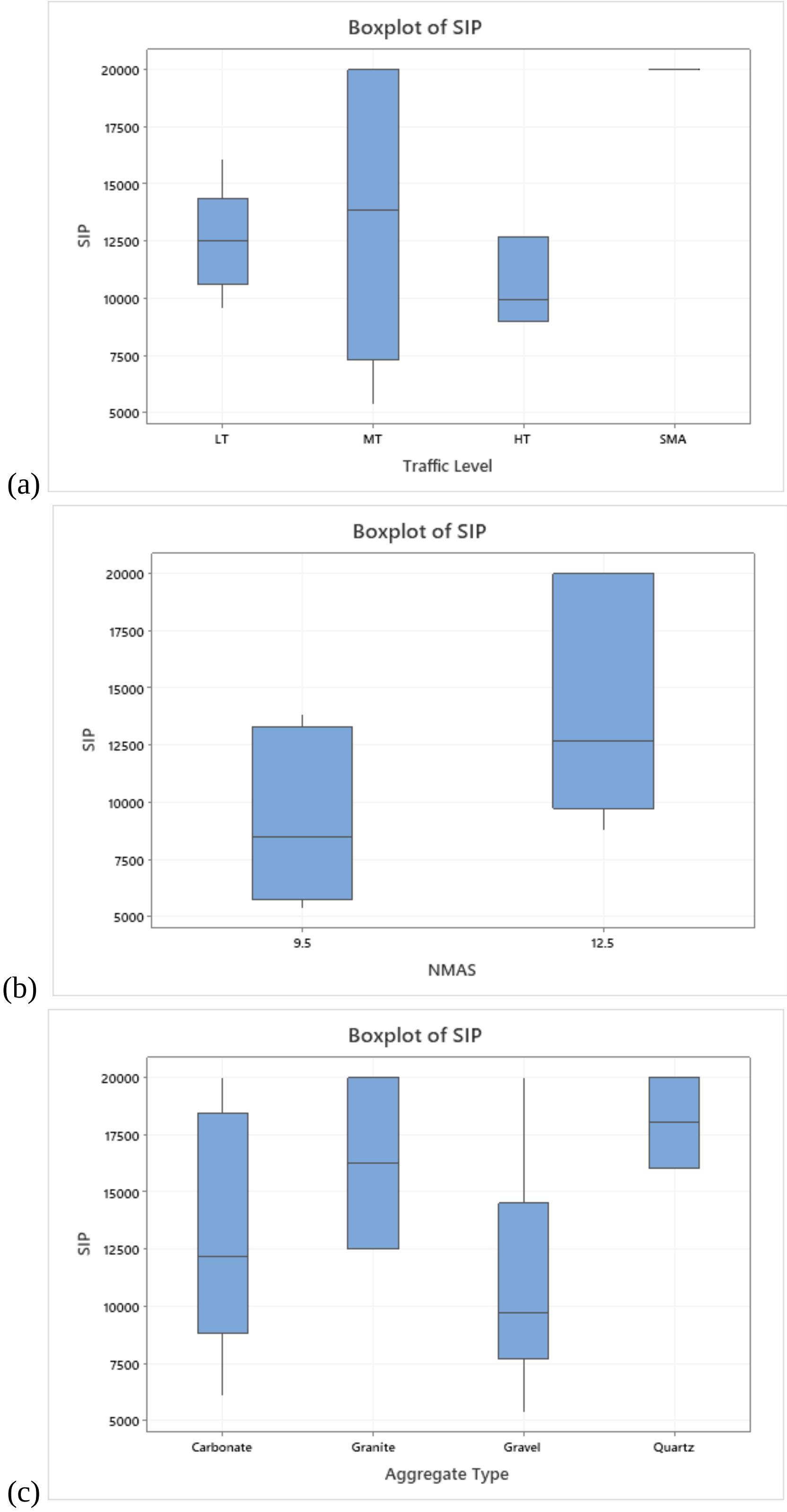

Figure C4. Boxplots of HWTT *SIP* Results at 46°C by (a) Traffic Level, (b) Aggregate NMAS, and (c) Aggregate Type

APPENDIX D. TEST RESULTS OF BMD OPTIMIZATION EXPERIMENT

Table D1. M – IDEAL-CT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	RAS (%)	Replicates	V_a (%)	CT_{Index}		
					Avg.	Avg.	St. Dev.	CV (%)
NCAT	5.3	PG 58S-28	0	5	7.1	35.4	7.7	21.8
NCAT	5.8	PG 58S-28	0	5	7.0	52.9	4.8	9.1
NCAT	5.3	PG 58S-28	3	4	7.3	30.6	4.5	14.8
NCAT	5.8	PG 58S-28	3	4	6.8	39.2	10.8	27.5
Contractor	5.3	PG 58S-28	3	5	7.2	25.4	5.7	22.6

Table D2. L – IDEAL-CT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	Rej. Dosage (%bwtb)	Replicates	Va (%)	CT_{Index}		
					Avg.	Avg.	St. Dev.	CV (%)
Contractor	5.8	PG 58S-28	0	5	6.9	36.0	5.4	14.9
NCAT	5.8	PG 58S-28	0	5	7.0	34.4	3.9	11.3
NCAT	5.8	PG 58S-28	3	5	7.1	51.7	6.8	13.1

Table D3. K – IDEAL-CT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	Replicates	Va (%)	CT_{Index}		
				Avg.	Avg.	St. Dev.	CV (%)
Contractor	6.5	PG 58S-28	5	6.8	27.5	4.1	15.0
NCAT	6.5	PG 58S-28	6	7.1	43.4	11.7	26.9
NCAT	7.0	PG 58S-28	5	7.0	59.0	5.7	9.6
NCAT	6.5	PG 52S-34	6	6.8	47.2	9.6	20.5
NCAT	7.0	PG 52S-34	6	6.8	79.3	15.5	19.5
NCAT	6.5	PG 58H-34	4	6.7	43.6	5.9	13.5

Table D4. C – IDEAL-CT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	LAS Dosage (%tbw)	Replicates	Va (%)	CT_{Index}		
					Avg.	Avg.	St. Dev.	CV (%)
Contractor	5.5	PG 58S-28	0	5	7.1	50.9	4.2	8.3
NCAT	5.5	PG 58S-34	0.5	5	7.2	32.2	3.0	9.2

Table D5. F – IDEAL-CT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	LAS Dosage (%tbw)	Replicates	Va (%)	CT_{Index}		
					Avg.	Avg.	St. Dev.	CV (%)
Contractor	6.4	PG 52S-34	0	5	6.7	60.6	5.8	9.6
NCAT	6.4	PG 58H-34	0.5	4	6.9	63.6	10.3	16.1

Table D6. M – DCT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	RAS (%)	Replicates	Va (%)	DCT G_f (J/m^2)		
					Avg.	Avg.	St. Dev.	CV (%)
Contractor	5.3	PG 58S-28	3	5	7.2	433	79.0	18.2
NCAT	5.9	PG 58S-28	3	6	7.0	476	75.9	16.0
NCAT	5.5	PG 58S-28	0	5	6.8	424	35.1	8.3

Table D7. L – DCT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	Rej. Dosage (%bwtb)	Replicates	Va (%)	DCT G_f (J/m^2)		
					Avg.	Avg.	St. Dev.	CV (%)
Contractor	5.8	PG 58S-28	0	5	6.8	349	36.0	10.3
NCAT	5.8	PG 58S-28	1.5	6	7.1	379	38.7	10.2

Table D8. K – DCT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	Replicates	Va (%)	DCT G_f (J/m^2)		
				Avg.	Avg.	St. Dev.	CV (%)
Contractor	6.5	PG 58S-28	5	6.9	310	61.5	19.8
NCAT	6.5	PG 58H-34	6	7.0	449	67.6	15.1

Table D9. C – DCT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	LAS Dosage (%tbw)	Replicates	Va (%)	DCT G_f (J/m^2)		
					Avg.	Avg.	St. Dev.	CV (%)
Contractor	5.5	PG 58S-28	0	5	7.3	292	56.3	19.3
NCAT	5.5	PG 58S-28	0	5	7.0	319	24.9	7.8
NCAT	5.5	PG 58S-34	0	6	7.1	356	39.5	11.1

Table D10. F – DCT Statistical Summary

Fabrication Lab	AC (%)	Binder Grade	LAS Dosage (%tbw)	Replicates	Va (%)	DCT G_f (J/m^2)		
					Avg.	Avg.	St. Dev.	CV (%)
Contractor	6.4	PG 52S-34	0	3	7.1	337	12.7	3.8
NCAT	6.4	PG 58H-34	0.5	6	7.2	416	64.8	15.6

Table D11. HWTT Analysis Summary – All Mixes – Average of 2 Replicates

Mix ID	Sample Description	Va (%)	AASHTO Analysis		Corrected Rut Depth Analysis	
		Avg.	$N_{12.5}$	*SIP*	CRD_{20k} (mm)	*SN*
M	Contractor-5.3% AC + 3% RAS	7.0	>20,000	16,063	3.4	>20,000
M	NCAT-5.9% AC + 3% RAS	6.9	>20,000	>18,500	4.3	>20,000
M	NCAT-5.5% AC – 0% RAS	6.7	>20,000	15,500	3.8	7,920
L	Contractor-5.8% AC–0% Rejuv.	7.1	>20,000	>18,000	2.7	6,076
L	NCAT-5.8% AC-1.5% Rejuv.	7.1	>20,000	>17,250	3.6	7,377
K	Contractor-58S-2-6.5% AC	6.8	13,800	8,800	4.1	2,253
K	NCAT-52S-34-6.6% AC	6.8	5,100	3,350	10.7	1,061
K	NCAT-58S-28 -6.8% AC	6.8	11,700	7,000	7.3	2,405
K	NCAT-58H-34-6.5% AC	6.8	11,400	6,600	5.1	2,319
C	Contractor-58S-28 -5.5% AC	6.9	19,000	12,688	3.7	3,579
C	NCAT-58S-34 - no LAS	7.6	10,000	6,000	4.2	1,665
C	NCAT-58S-34-0.5% LAS	7.1	15,100	7,250	3.9	2,439
F	Contractor-52S-34-6.4% AC	6.7	8,300	5,375	7.1	1,573
F	NCAT-52S-34 + no LAS	6.6	6,400	4,250	10.5	1,317
F	NCAT-52S-34 + 0.5% LAS	6.7	8,100	5,750	8.5	1,661
F	NCAT-58H-34 - no LAS	7.0	11,400	8,000	6.1	2,189
F	NCAT-58H-34 + 0.5% LAS	7.1	12,600	9,000	6.5	2,557